

**AN AUTOMATED COMPUTER
CONTROLLED ULTRASONIC ADHESIVE
BOND EVALUATION TECHNIQUE.**

RAISCH JACK WILLIAM
DEGREE DATE: 1977

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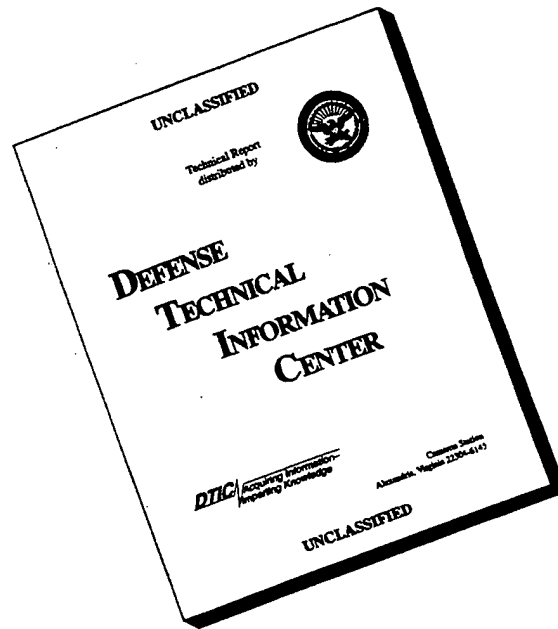
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Page: 1 Document Name: untitled

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-- 1 - AD NUMBER: D428393
-- 6 - UNCLASSIFIED TITLE: AN AUTOMATED COMPUTER CONTROLLED ULTRASONIC
-- ADHESIVE BOND EVALUATION TECHNIQUE.
--10 - PERSONAL AUTHORS: RAISCH, J. W.
--11 - REPORT DATE: 1977
--12 - PAGINATION: 104P
--20 - REPORT CLASSIFICATION: UNCLASSIFIED
--21 - SUPPLEMENTARY NOTE: THESIS SUBMITTED TO DREXEL UNIVERSITY IN
-- PARTIAL FULFILLMENT FOR PH.D.
--22 - LIMITATIONS (ALPHA): APPROVED FOR PUBLIC RELEASE; DISTRIBUTION
-- UNLIMITED. AVAILABILITY: UNIVERSITY MICROFILMS INTERNATIONAL, 300 N.
-- ZEEB RD., ANN ARBOR, MI. 48106. 77-22535.
--33 - LIMITATION CODES: 1 24

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An Automated Computer Controlled Ultrasonic
Adhesive Bond Evaluation Technique

A Thesis

Submitted to the Faculty

of

Drexel University

by

Jack William Raisch

in partial fulfillment of the
requirements for the degree

of

Doctor of Philosophy

June 1977

Thesis Approval Form



This thesis entitled An Automated Computer Controlled
Ultrasonic Adhesive Bond Evaluation Technique

and authored by Jack William Raisch

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RAISCH, Jack William, 1949-
AN AUTOMATED COMPUTER CONTROLLED ULTRASONIC
ADHESIVE BOND EVALUATION TECHNIQUE.

Drexel University, Ph.D., 1977
Applied Mechanics

Xerox University Microfilms, Ann Arbor, Michigan 48106

ACKNOWLEDGMENTS

The author gratefully acknowledges the guidance and assistance of his thesis advisor, Dr. Joseph L. Rose, during the course of this work.

Sincere appreciation is extended to the Air Force Office of Scientific Research for the financial support of this work. In addition, the use of the computer system on loan to Drexel University by Krautkramer-Branson, Inc. is greatly appreciated. The author would also like to thank the members of the ultrasonics research group at Drexel University, in particular Mr. Michael Aviolli and Mr. Morris Good for programming assistance, Mr. Graham Thomas for specimen preparation, and Mr. James Carson for helpful technical discussions and assistance. In addition, guidance from members of the faculty at Drexel University, in particular Drs. A. Wang, L. Bahar, B. Eisenstein, R. Koerner, and R. Mortimer, is greatly appreciated.

Finally, the author would like to thank his wife, Dolores, for her encouragement and enthusiastic support during the course of this work.

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ABSTRACT

An Automated Computer Controlled Ultrasonic
Adhesive Bond Evaluation Technique

Jack William Raisch

Dr. Joseph L. Rose - Supervising Professor

An inspection procedure for a step-lap joint problem is reviewed in detail in this report. Rather than study the mechanics of bonding and the relationship of performance to many manufacturing and service variables, it is proposed to examine the potential of selected ultrasonic signal features and their ability for predicting performance of an adhesively bonded structure. Emphasis is placed on studying the disbond type problem. Adhesive problems are considered; not cohesive. The adhesive problem is the one termed most critical with respect to inspection difficulty as mentioned by many individuals in Air Force and other government and industrial agencies. Adhesive or surface preparation problems on either one or both sides of a test specimen will be considered with emphasis being placed on the establishment of a one-sided inspection approach, because of the practical value of this inspection procedure. A completely automated data acquisition and analysis procedure is developed, not only because of the

fast convenient automation process, but because of its necessity in noise reduction and test repeatability in advancing the state of the art in this critical inspection problem. Complete information in a RF ultrasonic waveform is considered in this study with significant advancements being made in the application of Fourier transform procedures. In addition, several concepts and philosophies in pattern recognition are introduced, combined with various options and flexibilities in employing probability density function curves. Mechanics is used in the study by way of shear distribution analysis and theoretical wave interaction analysis with various models in assisting the pattern recognition program of study. In summary, various index of performance charts are presented with special attention being given to the fact that 85% of all extremely poor adhesively bonded test specimens can be reliably separated.

INTRODUCTION

The widespread use of industrial adhesives as critical structural components has increased greatly in recent years, in particular for joining metals to metals or metals to composite materials in the aircraft industry. Adhesives are often suitable for solving many joining problems compared to the more common techniques of welding, riveting, and the use of other mechanical fasteners. One of the major limitations on the use of adhesives as a structural element, however, is associated with the difficulty encountered in making an accurate determination of bond quality or potential performance after the joint has been completely assembled. A principal goal of this study is, therefore, to develop a nondestructive evaluation technique that makes use of a single ultrasonic measurement for predicting the potential bond performance level in a popular step-lap joint test specimen, as illustrated in Fig. 1. Rather than study the mechanics of bonding and the relationship of performance to many of the manufacturing and service variables outlined in a paper by Rose and Meyer [1], it is proposed to examine the potential of various ultrasonic signal features and their ability for predicting performance of an adhesively bonded structure. Emphasis in this work is placed on the adhesive problem compared to a cohesive one, and also the non-disbond problem compared to the disbond one. Problems on one or both interfaces will also be

considered with a goal of employing only a one-sided inspection procedure being critical because of its practical value.

Adhesive bonding is rapidly becoming a very necessary fastening technique. As an alternative to welding, adhesives may be used to join very thin materials to a thicker base metal without damage to the thinner material. Aside from the apparent saving in weight of a structure, an additional advantage obtained is related to the resistance to bimetallic corrosion created by the non-conductive properties of many industrial adhesives. Recent widespread use of composite materials has also prompted the need for adhesives. Both rivets and threaded fasteners require pre-drilled holes, which, even in metallic materials, introduce areas of high stress concentration resulting in cracking and possibly complete failure. When used in the joining of composite materials, adhesives distribute the stresses more uniformly than mechanical fasteners resulting in a higher load capacity for the structural element [2]. Many honeycomb sandwich panels, critical to the aircraft industry, could not be manufactured without the use of modern structural adhesives.

One of the major limitations of adhesive technology today is related to the difficulty associated with the nondestructive evaluation of a completed adhesive bond joint. With modern nondestructive testing equipment, the detection of voids or disbonds is not difficult. Many bonds

which apparently contain no voids or disbonds, however, appear to be good quality bonds, but fail at loads far less than the nominal strength of the adhesive. It is the detection of this interfacial bond strength that has created the problem of adhesive bond performance prediction. Zurbrick [3, 4] discusses the many variables that can affect the ultimate strength of an adhesive bond. Typical variables including bondline thickness and substrate surface condition. Correlation potential of these items with the performance of a completed adhesive bond were examined. This type of study, although necessary to the development of optimum bonding technology and conditions, is often not suitable for typical industrial applications today, because of the large number of design, manufacturing and in-service variables that exist for the bonding problem. A list of typical variables is included in Rose and Meyer [1]. Assuming that every parameter or variable could be monitored accurately throughout the entire substrate preparation and bonding process, reliability in acquiring consistently high quality bonds would still not be assured because of the possibility of contamination or equipment malfunction at any stage of the process. Again, therefore, for classification, a goal of this work is to acquire an ultrasonic measurement once the bond is completely manufactured, and to predict performance potential with a high degree of confidence.

A brief literature review on the subject of adhesive bond inspection is presented in the following paragraphs.

Rose and Meyer [5] have employed an ultrasonic evaluation technique to measure bondline thickness assuming the wavespeed of the adhesive layer is known. Using this technique, any thin layer such as a bondline may be measured accurately using the correlation of thickness and wavespeed to frequency depression spacing. Rose and Meyer [1] provide a substantial resource base in understanding manufacturing parameters, thickness measurement, and shear stress distribution in a step-lap joint. The development of modelling concepts for studying ultrasonic wave interaction with adhesive bonds is reported in Rose and Meyer [6, 7, 8]. Promise for solving the difficult performance prediction problem is illustrated in Meyer and Rose [9], where acid etch surface preparation on both sides of adhesive bond is eliminated to yield low strength bond specimens. Performance is then compared with ultrasonic bond echo signals for a properly prepared adhesive bond specimen. In this particular case, the single feature of ultrasonic bond echo amplitude to upper surface reference amplitude provides a reasonable correlation separating good and poor quality bonds. In this case, a 20 MHz transducer was necessary to show the required separation. Similar studies using a 10 MHz transducer did not achieve any high confidence level separation between the two bond quality classes.

Meyer [10] has developed extensive modelling concepts in an attempt to predict theoretically the ultrasonic response from a layered adhesive bond system. He concluded that several ultrasonic signal parameters could possibly be used to correlate with the adhesive integrity of bond - substrate interfaces. Current ultrasonic data acquisition limitations at the time of his work restricted actual measurement capability to bondline echo amplitude, which was found to correlate fairly well with adhesive strength using a 20 MHz ultrasonic signal. This work by Meyer showed promise for solving the adhesive bond strength prediction problem and served as a feasibility study for this work. Theoretical modelling of the effects of attenuation as a function of frequency on the physical condition of adhesive bonds is reported in Meyer and Rose [11].

Thompson, Alers and Thompson [12] have shown that it is feasible to relate the bond strength characteristics of the adhesive used to attach the skin to the honeycomb core in sandwich panels to the damping characteristics of panel vibrations and the propagation velocity of surface waves on the panel.

The cohesive strength prediction problem has been solved by Flynn [13] using measurements of wavespeed and attenuation in the bulk adhesive, provided that adhesive type failure did not occur. The bond strength prediction problem may be approached from either an adhesive or

cohesive point of view. The cohesive strength of an adhesively bonded system is not the most critical inspection problem, since normal structural adhesive failures at a low load are usually adhesive in nature. Cohesive bond strength is basically a property of the adhesive itself, and is usually altered by such items as improper cure, environmental degradation (such as moisture or thermal cycling), or aging. These processing and in-service parameters, although critical to the integrity of an adhesively bonded structure, do not normally result in extremely low load failure situations. The cohesive strength prediction problem of an adhesive bond layer has also been studied by Yee, Chang and Flynn [14] using ultrasonic spectroscopy measurements to characterize the physical state of the adhesive in a bonded laminate. The ultrasonic spectroscopy measurements are correlated to the wavespeed, attenuation and acoustic impedance associated with the adhesive. Other attempts to measure the cohesive strength of a bonded structure have been made in the past; the most notable being associated with the Fokker bond tester as discussed in Smith and Cagle [15]. The Fokker bond tester is an instrument used to correlate resonant frequency and vibrational amplitude to adhesive bond integrity. Although the Fokker bond tester does yield actual quality numbers related to the bond strength prediction, the instrument is not sensitive to interfacial conditions of the bonded structure.

The adhesive strength prediction problem has been studied extensively with little success to date. Chang et al [16] have attempted to correlate ultrasonic parameters of bond echo amplitude ratios and the half-amplitude bandwidth of spectral depressions to predict adhesive quality in a bonded structure. Using spectral depression spacing to predict bond thickness and x-ray inspection to detect actual voids, strength of the structure was predicted on a percentage area basis for non-uniform adhesive bonds and various gating levels. A variation in stress distribution over the bonded area was not considered, yielding a linear relationship between percent void area and percent strength performance. It was concluded that amplitude ratios of top and bottom bond echoes and spectral depression bandwidths may be indicators of bond strength on the limited number of actual samples tested. The need for more samples in an extensive testing program is clearly pointed out. Chang et al [17] show a theoretical development resulting in bond echo amplitude ratios and half-amplitude spectral depression bandwidths being related to acoustic impedances at the interfaces of a bonded joint. The theoretical work is based on a solution developed by Brekhovskikh [18]. Flynn [19], however, continued this approach and found no success in correlating these particular parameters with interfacial bond strength.

Alers and Graham [20] clearly point out the lack of success achieved in trying to correlate interfacial

strength performance with ultrasonic signal parameters using normal incidence pulse echo techniques. Because of the extremely thin adhesive - substrate interface, they felt that a technique using ultrasonic wave incidence parallel to the bondline enabling the wave to interact with the boundary for a greater length of time would yield conclusive results. Alers and Elsley [21] developed theoretical modelling to determine the effects of boundary conditions on waves propagating parallel to the bondline. They found that the lowest frequency vibrational resonance of the entire sandwich moved according to changes in the boundary conditions at the interfaces. This conclusion was experimentally verified with a limited number of specimens.

It might be pointed out that many workshops and conferences carried out throughout the United States during the last four or five years have continually pointed out the need for the establishment of a reliable inspection program for determining adhesive bond strength. In particular, emphasis has been placed on the interfacial strength problem. The National Materials Advisory Board Report [22] points out this need in detail. It also might be mentioned that the recent Rockwell ARPA/AFML Program [23] is concerned with studying the adhesive bond strength problem. This program is currently in progress, and many new investigators are currently entering the arena to study this problem. In addition, an Air Force sponsored program, the Primary Adhesively Bonded Structures Technology (PABST)

Program [24] has been initiated to study the numerous processing parameters effecting the service life of a bonded joint. As a secondary goal, the PABST Program makes use of admittedly inadequate state of the art nondestructive testing techniques to predict adhesive bond performance potential.

SHEAR STRESS DISTRIBUTION CONCEPTS IN ADHESIVE BOND INSPECTION

Shear stress distribution in a step-lap joint has been considered by Erdogan and Ratwani [25]. A complete derivation of their result is illustrated in Appendix A. A signal processing technique based on shear distribution was devised in this work to eliminate the unequal contribution effects of test signals. Although it is not the goal of this study to develop an exact and thorough formulation of the shear stress distribution based on mechanics and the study of elasticity, it is necessary to understand the state of stress and its implications in a step-lap joint under tensile loading.

Because the end sections of each adhesive bond joint must support a higher shear stress than the center section when the specimen is loaded in tension, an adjustment had to be made to compensate for possible quality gradients along the bond interfaces. For instance, in the event that the center section of the bond area was of poor quality, the total load carrying capability of the joint would not be affected as greatly as if the end sections were of poor quality. For this reason, a spatial weighting technique was devised to enable each ultrasonic signal to be correlated with an actual performance figure corresponding to the shear stress supporting requirements of that point.

Although the exact shear stress distribution in the step-lap joint may be calculated, the averaging effect of a finite area transducer removes the capability of performing exact spatial compensation from point to point on the bond area. For this reason, only the qualitative effects of the shear stress distribution have been considered in the spatial weighting technique applied to the final solution.

THEORETICAL MODELLING

Theoretical modelling was considered to assist in the feature extraction procedure necessary in the pattern recognition program of study. Feature extraction is a process of selecting specific features of an amplitude vs. time profile or some other transform profile.

Using a computer code previously developed and illustrated by Meyer [10] and Meyer and Rose [8], a series of computer runs were made to model the particular adhesive - substrate system being studied. By using a reconstruction of the actual ultrasonic pulse as the input to this three-layer system, and setting the bondline thickness to match experimental conditions, wavespeed in the adhesive itself was calculated using the spectral depression spacing. Once an accurate wavespeed was found for the bulk adhesive, variations on the surface conditions at the interfaces were modelled. Several series were run using area reductions on one or both surfaces of 25% and 50% in an attempt to correlate feature variations of the amplitude-time pulse and associated frequency profile to interface conditions.

As shown in Fig. 2, bond echo characteristics were obtained from several N-layer computer runs. Fig. 2A shows the bond echo from a layered adhesive system with 0% area reduction on both interfaces. Figures 2B and 2C show results from 25% and 50% interface area reductions,

respectively. If characteristics of the amplitude-time pulses are carefully measured and compared, it may be seen that a larger percentage area reduction effectively increases the amplitude of the returning echo. This conclusion may be drawn by measuring peak to peak amplitude of the bond echo. Although it may not be obvious from the computer result, the bond thickness is such that the returning echo from the bottom interface is not superimposed on the main pulse. This portion of the ultrasonic energy is generally delayed in time at least one wavelength for this 10 MHz pulse depending on the exact thickness of the bondline. Therefore, the trailing part of the pulse is indicative of the condition of the bottom or second bond interface. If peak to peak amplitude of the trailing cycles is measured with a constant top or first bond interface quality, it will be found that as the percentage area reduction of the bottom interface increases, the amplitude of this portion of the signal also increases. This effect may be seen by comparing Fig. 2A with Fig. 2D. However, since the amplitude of this part of the entire signal is dependent not only on the bottom interface quality but on the actual amount of energy transmitted through the top interface of the bond, the relative amplitude of this portion of the signal is highly dependent on the top surface and, therefore, on the peak to peak amplitude of the entire signal.

In examining the frequency profiles from bond echoes representing various quality bonds or various percentage area reductions at the interfaces, it may be seen that the frequency depression depth appears to be a valid indicator of surface condition. This depth as measured from the frequency profile, however, may also be dependent upon the frequency positions where the depths occur. For this reason, it is not only necessary to measure relative spectral depression amplitudes, but position of these depressions must also be calculated. In general, the spectral depression depth will depend upon the relative amplitude of the trailing portion of the bond echo compared to the peak to peak amplitude as may be seen by comparing Figures 2A and 2D.

Based on the above observations, several characteristic features were chosen including peak to peak amplitude, pulse duration, spectral depression depth, and spectral depression position, as likely characteristics of the bond echo related to potential performance to be used in the pattern recognition development.

GENERAL SUMMARY OF PATTERN RECOGNITION TECHNIQUES CONSIDERED

Several different approaches in pattern recognition were considered in this program of study, basic principles of which are described in Andrews [26], Duda and Hart [27], Mucciardi [28, 29], Rose et al [30] and Rose [31]. A brief summary of principle observations on several techniques is outlined in the following paragraphs.

Fuzzy Logic Technique

Fuzzy logic procedures similar to those considered in Rose et al [30] require the establishment of accurate probability density estimator (PDE) curves to be used in a probabilistic approach to the classification problem. In summary, the approach involves the determination of threshold values for each feature considered in the study which yields a high probability of correct classifications. The technique depends quite strongly on the availability of large amounts of data required for accurate threshold value selection.

Minimum Distance Classification

This standard technique in pattern recognition requires the establishment of a representative vector or group of vectors for each class distinction desired. The vectors may be simply a reconstruction of the amplitude-time signal, the associated amplitude-frequency profile, or may be made

up of a list of non-linear features extracted from each representative signal or transform of the signal. After vectors have been established as representative of each class desired, a test vector is then compared with each of the training vectors used. The training vector lying closest to the test vector, using a minimum distance calculation, becomes the classification prediction for that test vector. For this technique to work well, a reliable physically motivated class system must be established. For instance, if it is desired to separate the data into two groups - when in reality the two groups desired are actually composed of three or more sub-classes - the minimum distance classification will not work unless the sub-classes are known and established in the algorithm.

Linear First-Order Adaptive Learning Network

This approach may be used to simplify the visual interpretation of clustering of certain features. For example, if eight features, x_1, x_2, \dots, x_8 , are selected to form a vector representing a particular training classification, they may be combined in a linear fashion as follows:

$$y_1 = a_1 x_1 + a_2 x_2 + a_3 x_3 \quad (1)$$

$$y_2 = a_4 x_4 + a_5 x_5 + a_6 x_6 + a_7 x_7 + a_8 x_8 \quad (2)$$

where x_1, x_2 and x_3 are physically similar features and x_4 through x_8 are associated in the same way. The "a's" are coefficients to be determined by adjustment. Basically,

this approach provides two modified features, y_1 and y_2 , of which a good prototype and a poor prototype could be calculated if, for example, a two-class problem were considered. This allows the examination of natural clustering in a two-dimensional feature space rather than the previous eight dimensions. Adjusting the "a" coefficients may provide an improvement in the classification capability of the system. In addition, the approach has merit in the case where single features show very little clustering, but feature interaction exists. Also, adjusting the "a" coefficients with an inverse feature or with a product of features could prove worthwhile.

Non-Linear Adaptive Learning Network

A layered network similar to the type described by Mucciardi [28, 29] may also be considered in a pattern recognition program of study. In this technique, combinations of two features, x_1 and x_2 , are considered for clustering capability when combined in the following fashion:

$$y_1 = a_1 x_1 + a_2 x_2 + a_3 x_1^2 + a_4 x_2^2 + a_5 x_1 x_2 + a_6. \quad (3)$$

Every combination of features is checked in this way for the clustering capability and the best performing combinations are chosen to form the first layer of the network.

Assuming five such high performance combinations were found, the first layer would consist of five boxes resulting in five "y" outputs, y_1 through y_5 . In the same way,

combinations of y_1 through y_5 are formed two at a time, and the best performers are chosen to form the second layer of the network. This procedure is followed through several layers until a sufficiently high performing end result is found. The difficulty with this type of system lies in two areas; first, a suitable training set must be found using PDE curves to establish reasonably representative vectors for each class desired. Then a selection set must be formed also from representative vectors to use in determining the highest performing feature combinations. Secondly, as the number of layers in the network increases, the order of the curve fitting function increases requiring larger data sets to assure that the network is not approaching the order of the data.

Combined Approaches

Various combinations of the above techniques may be used to make a series of decisions or partial decisions for forming a complete bond classification algorithm. As shown in Fig. 3, assuming that a fuzzy logic decision can be made for at least partial separation, it may be used as a filter for directing the extreme data to one of several classes. In the case of the bond sorting study, as an example, an adaptive learning network (ALN) may not be found that can classify a large percentage of the data over all three classification ranges. However, it might be possible to find an ALN that would perform well over a single range

only, and give unrealistic responses for data outside of that particular range. If an ALN could be found for each of the three bond classification ranges, the data could be fed to each of the three components of the system, and a logic circuit could be used to determine the single resulting realistic prediction. A fuzzy logic sorting algorithm could be used before this type of three-fold network is used, determining either extremely high or low quality bonds, since a threshold for these conditions may be much easier to determine than an actual exact classification threshold.

If it were possible to determine a fuzzy logic algorithm that would reliably classify the bonds, a system similar to that shown in Fig. 4 could be used for two principle reasons. The fuzzy logic could be used as a switch to direct the data to only one of the three ALNs. This would be useful if an actual quantitative failure load was desired in the prediction. In addition, it would supply an additional check on the decision made by the fuzzy logic algorithm. For instance, if the algorithm directed the data to the ALN designed for the high quality range, and that ALN predicted a failure load either unrealistically high or lower than the lower bound of the high range, the fuzzy logic decision could be questioned.

Many variations of this type of logic using different pattern recognition techniques as elements in a complete pattern recognition system exist. No single algorithm

must be found which completely characterizes the entire physical system. If reliable decisions can be made on small portions of the system, it is feasible to combine these decisions in series or parallel to produce a complete classification system.

EXPERIMENTAL DETAILS

Introduction

An ultrasonic pulse echo immersion system was chosen for the data acquisition system required in this study. A block diagram of the system is shown in Fig. 5. The ultrasonic signal is fed from the pulser - receiver unit to an analog to digital (A/D) converter where it is digitized and stored in the converter's memory. The digitized data is then transferred to the memory of the computer via controlling software. In addition, a computer driven x-y scanner is used to position the transducer over various data acquisition points on the specimen. The software written for the data transfer and scanning systems is fully automatic requiring no input from the operator during the data acquisition sequence. After the data is collected and analyzed, and bond quality prediction has been made, the specimen is removed from the immersion tank and destructively tested. Additional details of the experimental system and test specimen details are outlined in the following paragraphs.

Test Specimen Description

Several series of test specimens have been fabricated for this study. A typical step-lap specimen is shown in Fig. 1. Two industrial adhesive systems, FM-47 and FM-73, from American Cyanamid Co. were used in this study.

Manufacturing techniques for each adhesive system are illustrated in the following paragraphs.

Each substrate was machined from aluminum bar stock so that its finished dimensions were 8" X 1" X 1/2". A hole was drilled in the end of each half opposite the joint for mounting in an Instron testing machine for tensile strength evaluation. A one-inch long step was cut into the other end providing a total bond area of one square inch with a nominal bond thickness of .01 inch for FM-47 and .005 inch for FM-73 specimens.

Surface preparation of the adherends is the first step in adhesive bonding. It is important to clean thoroughly all surfaces which will be in contact with the adhesive. To accomplish this, the following procedure was followed:

- 1) The aluminum specimens were first wiped free of grease, oil, and dirt with acetone and then rinsed with tap water.
- 2) A test for water break was done at this point to determine surface contamination. The water usually beaded at this time, indicating need for further cleaning.
- 3) Specimens to be etched are then immersed in a chromic-sulfuric solution for ten minutes.
- 4) After ten minutes, the etched specimens are rinsed in cold tap water and soaked in cold de-ionized water for five minutes. During this step, the water break test will show a smooth continuous sheet of water over the etched areas.
- 5) Upon removal from the de-ionized water, the specimens are dried in a vented oven at 145°F. This cleaning procedure is the same for

both FM-47 and FM-73 adhesives. In each series of specimens, the surface treatment was varied by eliminating the acid etch from certain specimens, and in some cases by contamination of the bonding surface of the substrates.

After the specimens have dried, they are removed from the oven and allowed to cool to room temperature. After cooling, a thin layer of the appropriate primer is sprayed on the specimen surfaces which are to be in contact with the adhesive. For the FM-47 adhesive, the primer layer (FM-47 primer) should be .001 to .003 inches thick and for the FM-73, the primer layer (BR-127) should be .001 to .002 inches thick. The primer is first dried at room temperature, for two hours in the case of FM-47 and for thirty minutes in the case of BR-127. Then the specimens are placed in a vented oven to complete the primer cure cycle. The FM-47 primer is cured for sixty minutes at 230°F and the BR-127 primer is cured for thirty minutes at 250°F.

The actual bonding of the two aluminum half specimens is done in an autoclave. Both adhesives, FM-47 and FM-73, are manufactured in large sheets with a skim. The sheets may be cut to the appropriate size and shape, in this case, one inch squares. The adhesive squares are placed on the bonding surfaces and the specimens are placed in a jig for curing. The specimens are then sealed in an acetate bag, placed in an autoclave and attached to a vacuum line. A vacuum of 28 to 29 inches mercury is drawn on the bag as

the temperature is increased. To cure FM-47, the specimens are heated to 280°F, at which point the autoclave is pressurized with nitrogen to obtain an effective bonding pressure of 100 psi. Heating is continued until the temperature reaches 300-335°F, and is held at that temperature for thirty minutes. The specimens are then allowed to cool to 210°F under full pressure. At 210°F, the pressure and vacuum are released and the specimens are removed from the autoclave and allowed to cool.

FM-73 cure cycles need not be controlled as rigidly as those for FM-47. The following cure cycle chosen for this study is within the specifications outlined by American Cyanamid. After bagging, the specimens are heated to 250°F within thirty minutes in an autoclave. The vacuum is drawn and autoclave pressure is applied until the effective bonding pressure is 40 ± 5 psi. The specimens are held at 250°F for sixty minutes and then allowed to cool to 200°F under pressure before they are removed from the autoclave.

After the specimens are removed from the jig, they are waterproofed by coating the bondline edges with polyurethane. This waterproofing is applied to eliminate the possibility of water affecting the bond during ultrasonic inspection in an immersion tank.

Ultrasonic Test System

Because the data is analyzed completely in the computer, only a very simple ultrasonic instrumentation system

is required. The system consists of an Aerotech UTA2 Pulser/Receiver driving a 1/4" diameter straight beam highly damped transducer. The transducer is mounted on a fixture attached to the x-y scanner and scans the bond specimen through a 1.5" water path. Oscilloscopes shown in the block diagram are not necessary to the operation of the system, but were used only to monitor the signal during various stages of the data acquisition routine.

Computerized Data Acquisition System

The entire data acquisition system for bond inspection is developed around a Digital Equipment Corporation PDP 11/05 Minicomputer with 32K core memory. Peripherals include a RK05 disk drive, dual cassette drives, a Dec-writer teletype and line printer, and a Tektronix 4014 video terminal and 4631 hard copy unit. The disk is used to store the operating system for the computer and all software packages required for data acquisition and analysis. Cassette drives are used mainly for data storage.

The A/D converter is a Biomation 8100 unit capable of sampling intervals to .01 μ sec. Digitizing at this sampling rate will yield approximately 10 points per cycle on a 10 MHz pulse. The converter digitizes to an accuracy of 1 part in 256, and can store 2,048 amplitude-time points in its memory at one time. The A/D converter has been interfaced to the minicomputer through a DR11-C general I/O interface board. After digitized data is stored in

the computer, an interpolation routine is used to reconstruct the signal.

Computer Controlled Scanning System

Since each bond specimen must be scanned, and data taken at various points from the bond, a computer controlled x-y scanner was designed and constructed and is shown in Fig. 6. Each axis of the scanner consists of a stepping motor running at 200 steps per revolution connected to a lead screw with a pitch of 20 threads per inch. The lead screw rotates in a threaded teflon bushing anchored to the transducer holding fixture. Electronically, one step of the motor translates to .00025 inches. The stepping motors are driven through control panels, which translate specific bit patterns from the computer to sequenced pulses suitable for the stepping operation. The control panels are interfaced to the computer through a DR11-M output interface board.

Destructive Test System

Within minutes of completing an ultrasonic test sequence, the bond specimen is destructively tested on an Instron Model 1230 tensile testing machine. The specimens are held with pin grips through the holes in each end and loaded in tension until failure. Strain rate was kept at .01 inches per minute. Each specimen prepared using the prescribed surface treatment failed cohesively, with portions of the adhesive and scrim cloth remaining on both

adherends. In every case, those specimens subjected to an improper surface preparation during manufacture appeared to fail adhesively, exhibiting a clear separation of the adhesive from one or both adherends. Load vs. displacement was recorded on an x-y plotter for each specimen.

Data Acquisition Procedural Details

After a bond specimen has been placed in the immersion tank and transducer alignment and pulser controls set properly, the data acquisition program SCAN is called into the memory of the computer. The program arms the A/D converter, which then waits for a signal to trigger the converter to begin a record cycle. The trigger for the A/D converter is actually the gate display signal from the pulser. After completing a record cycle and capturing the reference pulse from the top of the specimen, the converter is then directed to transfer that portion of its memory contents containing the reference pulse to the computer. At this time, a sum of the squared error function is calculated against a standard reference pulse already stored in the computer, and peak to peak amplitude of the pulse is calculated. The computer then sets appropriate time delays and input sensitivities on the converter and starts the record cycle again; this time to record the bond echo. After digitizing and recording the bond echo, the digitized data is then transferred to the computer and stored along with the sum of the squared errors and peak to peak ampli-

tude of the reference pulse. After the data has been stored, the computer directs the scanner to move to a new position, and the reference pulse recording begins over again. The scanner positions the center of the transducer at six different points over the surface of each bond specimen. These points are located at coordinates (.25, .25), (.50, .25), (.75, .25), (.75, .75), (.50, .75), and (.25, .75) shown in Fig. 7 on the surface of the 1" square bond area. After the data transfer has taken place at each of the six locations, the scanner returns to its starting position, and all six digitized bond echoes with their accompanying location coordinates and reference pulse characteristics are stored in a permanent data file.

EXPERIMENTAL TEST DEVELOPMENT DETAILS

Five series of aluminum to aluminum adhesively bonded test specimens were fabricated to provide for a step by step development of the computerized ultrasonic evaluation system. Conditions and results for each test series, including improvements for each of the following series, are included in the following sections.

Test Series I

A .010" thick commercially available industrial adhesive, FM-47, was used with 2024 T4 aluminum substrates in preparing twelve bond specimens for this series. Acid etch, as described in the test specimen fabrication section, was eliminated in certain cases in an attempt to obtain a distribution of failure loads on which classification could be based. Fig. 8 shows the results of failure load vs. quality rating for Series I, II and III bond specimens. Quality rating designations are 1 for properly prepared specimens, and 2 and 3 for specimens lacking the acid etch surface treatment on one and both substrates, respectively. As can be seen from the figure, although quality rating may be a valid statistical classification technique, variations in failure load are not sufficiently clearly separated by the quality rating classes to warrant this type of approach. It was therefore decided to attempt bond quality classifi-

cation based on failure load alone rather than preprocessing parameters affecting surface treatment.

A six-point data acquisition procedure was established during this series and also used throughout all five test series. However, Series I data was not processed using a spatial averaging technique. This data was analyzed by choosing only amplitude-time and amplitude-frequency profiles determined as typical by the operator for further data analysis work.

Feature extraction from the selected typical profiles was performed by the operator from graphics output from the computer. Emphasis was placed on three non-linear features of the amplitude-time and the amplitude-frequency profiles. One of the features chosen was peak to peak amplitude of the bond echo divided by peak to peak amplitude of the front surface reference echo in an attempt to duplicate previous results from [10]. No correlation was established between this feature and failure load, probably due to the introduction of non-uniform specimen preparation on opposite interfaces of the bond area. Other features considered were the number of discontinuities in the amplitude-frequency profile between 5 and 10 MHz, and the amplitude ratio of the first negative lobe to the second negative lobe in the amplitude-time bond echo.

A single reference echo was recorded for each data set of six bond echoes. This reference served only to

insure the consistency of the ultrasonic equipment, but was no indication of point to point surface irregularities on any given specimen. A very crude visual acceptance criteria on the transducer was employed in this series.

Test Series II

Twelve test specimens were used in Series II in an attempt to improve the data acquisition system. It was obvious from Series I data that great improvements in the area of noise reduction and reference signal acquisition were necessary. In addition, the visual determination of a typical signal from the six available amplitude-time signals from each bond surface was inadequate.

Primary sources of noise and distortion in the data acquisition system are shown in Fig. 9. Considering the input to the material system to be standard or unchanging, differences in the material or the flaw, in this case the bondline interfaces, produces a measure of distortion. Standard ultrasonic instrumentation introduces noise resulting from state of the art limitations in electronics, which may be termed "measurement noise". In addition, the use of an A/D converter introduces irregularities which may be termed "quantization noise" due to the procedure of applying a discrete value to evenly spaced points in an analog signal. A great improvement in signal to noise ratio was obtained in Series II by reducing the attenuation in the receiver amplifier of the pulser/receiver unit and

reducing the sensitivity of the input amplifier on the A/D converter.

Rather than recording a signal reference echo from each 1 square inch bond surface, a reference echo was obtained for each amplitude-time bond echo recorded. This reference echo did not only reflect any variations in the ultrasonic transducer or associated electronics, but recorded any change in surface condition of the top of the aluminum specimen.

Multiple data sets were acquired from each side of each bond specimen to insure repeatability of the data acquisition system. Rather than using a visual technique of selecting a typical bond echo from the set of six data points, a spatial averaging technique was used to combine selected features depending upon the position of the transducer over the bond area at the time the signal was acquired. As in Series I, the feature extraction was done by the operator from the graphics output of the computer. The main feature considered was based on relative amplitude ratios of peak to peak amplitude and amplitude of portions of the bond echo representing reflections from the bottom bond interface.

Test Series III

Thirteen test specimens were fabricated according to the guidelines established for Series I and Series II test specimens. A new transducer was used and computerized

feature extraction was introduced to the data acquisition and analysis system. A reference signal was obtained for all test points corresponding to each bond echo similar to the procedure in Series II.

It was noted from the data of Series I and II that the most outstanding shortcomings of the data acquisition system as it existed were associated with certain characteristics of the transducer. Amplitude-time profiles of the reference pulse were approximately 2 1/2 full cycles, resulting in a frequency profile slightly less broadband than desired. In addition, any ringing in the transducer which could be eliminated was considered desirable as complete time separation of top and bottom bond interface echoes would be facilitated with a shorter pulse. For these reasons, a 10 MHz 1/4" diameter straight beam, alpha series, Aerotech transducer was selected after being tuned by the manufacturer to the characteristics of the pulser/receiver existing in the data acquisition system. An amplitude-time and amplitude-frequency profile of the reference pulse is shown in Fig. 10. This transducer yielded a very broadband pulse of approximately 2 cycles and had a sensitivity roughly 4 dB higher than the unit previously used. It was intended to use this transducer for all future work in this study.

A computerized feature extraction technique was introduced which made use of the smoothing characteristics of a spline fitting interpolation routine. Details of

the procedure are shown in Fig. 11. After the data is collected from the six points on the bond specimen, each amplitude-time signal is smoothed using a spline function interpolation procedure outlined in Appendix B, and more completely illustrated in Greville [32].

The data acquisition method used for the feature extraction determined 13 features from each point of the ultrasonic bond scan sequences. These features may be divided into two categories, one being the features extracted from the amplitude-time domain and the second, those features obtained from the amplitude-frequency domain. The features extracted from the amplitude-time domain were defined as follows:

PTP - The peak to peak pressure variation represents the maximum amplitude variation among adjacent lobes of the amplitude-time bond echo divided by the maximum pressure variation of the reference signal.

ARG - The activity region is a modification of the term "pulse duration". To determine the activity region, a spline curve containing all the relative maximums of the rectified bond echo was found. Next, two points on the splined curve were located. They were the first and last points having an amplitude equal to a threshold value 5% of PTP. The difference in time of these points is the activity region.

ERAT - The area enclosed by the rectified amplitude-time bond echo within the activity region.

EAT - The ratio of positive to negative area enclosed by the amplitude-time bond echo within the activity region.

The remaining nine features were found by analysis of the amplitude-frequency domain. Since many of their definitions are dependent on one another, the features are defined in the order that the computer determined them.

The first parameter found by the computer is A_3 , the maximum amplitude of the Fourier spectrum. The computer next searches the Fourier spectrum to find a 6 dB down point on each side of the frequency location of A_3 . The difference between the 6 dB down frequency locations is defined as the 6 dB down bandwidth of the bond echo. The number of relative maximums and minimums occurring within the bandwidth region of the spectrum is defined as the number of relative maximums and minimums. Working outward from each 6 dB point, a number of relative minimums and/or maximums usually occur in the amplitude-frequency domain. The first relative minimum lower in frequency than the left 6 dB down point is A_2 . After passing A_2 and still proceeding towards zero frequency, the first relative maximum found is A_1 . Similarly defined is A_4 and A_5 which are higher in frequency than the right 6 dB down point. A_4 is a relative minimum and A_5 is a relative maximum. If

either A_1 , A_2 , A_4 , and A_5 are not found, they are assigned the value of the last Fourier amplitude analyzed while moving to the left or right of the respective 6 dB point.

For example, if both A_1 and A_2 do not exist, then

$A_1 = A_2 = C_{\text{begin}}$ where C_{begin} is the first Fourier coefficient in the search area. Thus, the remaining features may be defined as follows:

A_3/A_1 - the amplitude ratio of A_3 to A_1

A_3/A_5 - the amplitude ratio of A_3 to A_5

A_1/A_2 - the amplitude ratio of A_1 to A_2

A_5/A_4 - the amplitude ratio of A_5 to A_4

FREQ2 - the frequency location of A_2

FREQ4 - the frequency location of A_4

NRMM - the number of relative maximum and minimum

between the 6 dB points on both sides of A_3

BDW - the difference in frequency between the right 6 dB point and the left 6 dB point

MDF - the average frequency of the two 6 dB points

After the feature extraction software is applied to each bond echo, the thirteen features are combined into feature vectors, one for each bond echo, and are then averaged using the spatial averaging technique explained in the final results.

Several approaches to pattern recognition were considered in this study. A series of PDE curves were run on each feature to determine which features might be suitable for separating the data. It was found that although some

features looked promising when run for each class - good and bad - separately, it was impossible to set threshold values to yield good separation. These results indicated that there may be an interaction between features that cannot be defined without more advanced pattern recognition algorithms.

In performing a two-class problem, the specimens were grouped such that those failing above 2500 lbs. were Class 1 and those below 2500 lbs. were Class 2. Prototype feature vectors were formed using the mean value of each feature over all of the data for each class. A low index of performance on this self test indicated that additional sophistication in the pattern recognition algorithm was required. A further attempt to solve the two-class problem using weight selection was unsuccessful indicating that the two classes were not linearly separable.

Because one of the goals of this study is one-sided classification, that is classification of the bond using data from only one side, it was decided to expand the problem to a four-class problem. A four-class system is physically motivated by the fact that weak bonds may fail at a low load due to a problem at either the top or bottom adhesive-adherend interface, or at both interfaces. These differences would show up in the ultrasonic echo, but not necessarily in the failure load data. In addition, good bonds which fail at high loads may produce varied ultrasonic responses. For these reasons, the specimens were

grouped in four classes, two good and two bad. The index of performance for this four-class problem was extremely low using the minimum distance classifier. A linear discriminant function using weighting factors was sought but proper weights could not be established, indicating that the data is not linearly separable into four classes.

A thirteen-class problem was then attempted using the linear discriminant algorithm. In this case, each bond specimen represented one class. Weights were established using half of the data available and then a test was run using the remaining data. Index of performance figures were high. Although the test was unrealistic from an engineering viewpoint, hope was established in the separability of the data.

The two-class problem was then attempted using two adaptive learning procedures. A linear first order technique using the eight best features chosen by physical motivation and probability density function variations was attempted. In this case, weights for each feature were chosen by the operator in an iterative process looking for the highest index of performance. Final results were poor, resulting in an index of performance of about 60%.

The second adaptive learning procedure to be used considered non-linear combinations of sets of features. In this technique, the performance of combinations of two features is evaluated to find the combinations yielding the lowest error. Then, those sets of features chosen

are combined in the same way in a layering sequence. After two layers, index of performance values as high as 90% were obtained as a self test.

Test Series IV

Test Series IV consisted of 26 adhesively bonded specimens manufactured with a more recently available and popular adhesive, FM-73, which was chosen because of its current wide use in such Air Force applications as the PABST Program [24]. As before, application of the acid etch to one or more of the substrates was used to control the quality of the bond. In addition, specimen numbers 45 through 48 were exposed to contaminants before bonding. The contamination was accomplished using a silicon release agent, commonly used on fixtures ordinarily found in industrial bonding situations.

Due to the apparent failure of all of the pattern recognition based attempts at classification considered in Series III, the feature extraction approach was modified to yield more meaningful features and feature relationships as suggested by the initial PDE curves carried out in Series III. It was anticipated from both the computer modelling runs and the Series III test data that specific feature characteristics of the spectral depressions would be useful in a classification algorithm. However, none of the 13 features, many of which were associated with spectral depression depth and spacing, appeared to be sufficient for

data separation. It was realized that due to minor thickness variations from specimen to specimen, the spectral depressions moved in the frequency domain to such an extent that depth measurements became meaningless in the extreme cases where the depressions occurred far away from that portion of the amplitude-frequency profile containing peak energy. A transducer compensation technique where a normalization of the amplitude-frequency profiles is performed was not considered in this program of study.

Three new features were therefore derived from seven of the existing amplitude-frequency features. The procedure is detailed in Fig. 12. The center frequency of the 6 dB down line was considered as a starting point in determining the peak energy area for each signal. Spectral depressions characterized by A_2 and A_4 occurred lower and higher, respectively, of the center frequency in the frequency domain. A preliminary calculation is made to determine which spectral depression, A_2 or A_4 , occurs closest to the center frequency and, therefore, closest to the peak energy area in the signal. It is this depression that was chosen as the depression to be measured and correlated with bond strength. For every amplitude-time signal and its associated frequency profile, either A_2 or A_4 is chosen, and the frequency difference between the chosen spectral depression and the center frequency of the 6 dB down line is used as a first feature β_1 . If the depression at A_4 is used, features β_2 and β_3 become A_3/A_4 and A_5/A_4 ,

respectively. If the depression at A_2 is chosen, features β_2 and β_3 become A_3/A_2 and A_1/A_2 , respectively. Although the frequency difference between the center frequency and the location of the spectral depression used is normally used as a feature indicating cohesive bond strength, it is used here as a compensating feature in combination with features β_2 and β_3 to treat the non-uniform energy distribution over the bandwidth considered.

By constructing PDE curves for these three features, it is then possible to determine thresholds on each feature when used on an interactive basis with the remaining two. Fig. 13 illustrates the technique of using PDE curves in separating the data into a three-class system. The classes chosen were low (0 to 2,000 lbs.), medium (2,000 to 3,500 lbs.), and high (over 3,500 lbs.). As may be seen from Fig. 13, thresholds for feature β_1 may be chosen at 2.55 and 2.74 for a high class bond and between 2.05 and 2.50 for a medium class bond. Similar studies were made for the remaining classes and features considered with thresholds shown in Table 1. Exploring the possibility of feature interaction, features β_1 , β_2 and β_3 were plotted against one another in the three possible combinations for each set of bond data in the series. Data not falling within the designated thresholds, may not be classified using this approach. If any data falls outside of the range of the existing data altogether, it is also considered not able to be classified. For all specimens

considered in Series IV, an overall index of performance of 94% was obtained using this technique. Classifications and failure loads are shown in Table 2.

Test Series V

Series V data consisted of 29 specimens fabricated in a fashion similar to Series IV; a balance of properly prepared specimens expected to yield high failure loads, unetched on one or both substrates expected to yield medium failure loads, and contaminated specimens expected to yield low results was established. This balance, however, was not achieved due to quality control variations in the bonding procedure. Predictions and failure loads are shown in Table 3. Only a single specimen existed in the high failure load range, along with six specimens in the low range. It might be pointed out that specimens 118 through 124 were purposely contaminated in an attempt to provide representatives of the low load category. However, three of these - specimen number 120, 121 and 122 - all failed at medium loads and were correctly predicted.

A summary of the data spread for Series IV is shown in Table 4A, for Series V in Table 4B, and for the combined Series in Table 4C. It may be concluded that the performance of the classification algorithm is similar in both Series IV used as a training set, and Series V used as a test set. Possibly, PDE curves could be made from the combined data sets to yield better performing threshold levels for classification.

FAILURE MODES

In every series of specimens manufactured for this study, an attempt was made to create substandard surface conditions which would result in an adhesive failure well below the cohesive strength of the adhesive. As a check on the validity of the test specimen preparation effects on the failure modes, photographs were taken of representative failure surfaces for each type of failure mode encountered. Fig. 14A shows a typical cohesive failure where portions of the adhesive remained on each substrate. These specimens were prepared according to manufacturer specifications. Fig. 14B is a photograph of a surface showing a completely adhesive failure in a situation where the substrate was not etched with chromic acid prior to assembly. In this case the metal is clean, showing no traces of the adhesive remaining on the substrate.

SUMMARY OF SOLUTION

It may be seen from Table 4 that an index of performance of 84% was obtained using Series IV as a training set and Series V as a test set. A summary of the elements contributing to the solution is outlined in the following paragraphs.

Pattern Recognition Algorithm

As a last solution obtained in this study, Fig. 15 shows schematically the data analysis path possibilities. The input data enters a fuzzy logic network with thresholds set on the peak to peak amplitude of the bond echo divided by the peak to peak of the reference echo. It is known that a high peak to peak amplitude is indicative of a low quality interface, and a low peak to peak amplitude results from a high quality interface. Although an absolute threshold is difficult to set, the extreme high and low amplitudes may be sorted out as either very good or very bad bond interfaces for very low and very high amplitudes, respectively. Signals which are not sorted out at this stage, pass through to each of three interactive Bayesian type decision networks. The first combined features β_1 and β_2 , the second features β_1 and β_3 , and the third features β_2 and β_3 . Each network produces a decision based on the PDE curves for the two features considered in that network. Decisions may be high, medium, low,

no decision, or out of range from each network. After each network makes a decision, the three predictions are considered in a committee type vote situation, where the majority answers rule. In other words, if two high and a medium are predicted, the final prediction is high. If no prediction is duplicated, the lowest quality prediction prevails.

Reference Pulse - Signal Acceptance Criteria

Every amplitude-time signal to be stored in the computer and used for bond strength evaluation is accompanied by a reference pulse from the top surface of the aluminum specimen. This reference pulse is digitized, transferred into the memory of the computer, and compared point by point with the standard reference characterizing the transducer. The squared errors of each point from the standard reference are summed to give a total sum of the squared errors for the reference pulse. This number may be compared from specimen to specimen or location to location on each specimen. This method enables the operator to observe a numerical indication of the consistency of the ultrasonic data acquisition system. In addition, the peak to peak amplitude of each reference signal is stored in the computer along with the bond echo. This reference peak to peak amplitude is used to compare to the peak to peak amplitude of the bond echo to obtain a dimensionless feature.

Since the reference pulse is digitized during a separate cycling of the memory of the A/D converter, it is possible that unwanted noise may occur during the recording of the bond echo. Therefore, acceptability of the reference signal does not necessarily indicate acceptability of the bond echo. For this reason, it may be possible to obtain an apparently acceptable reference echo followed by a completely unacceptable bond echo. However, if the thresholds for the pattern recognition algorithm as stated in Table 1 are adhered to, unacceptable bond echoes will usually result in feature vectors lying out of range. In this case, no decision is made, and it is advisable to repeat the data acquisition procedure to obtain more suitable bond echoes. In certain instances, repetitive data acquisition attempts will not yield a feature vector within range. Therefore, it must be stated that certain bond and interfacial conditions exist that will not be classified by this technique. Considering the specimens encountered in Series IV and Series V, roughly 9% were of this type.

Spatial Averaging

A step-lap bond specimen was chosen for this study using 1/4" thick aluminum adherends in an attempt to subject the bondline to a nearly pure shear stress. Due to the peak shear stress occurring on the ends of the bondline, bond echoes from these points will carry more

weight in the final evaluation of the bond performance under a shear loading. For this reason, the six bond echoes from each specimen must be averaged using weighting factors which would maximize the influence of the end locations and minimize the influence of the center locations. Although the stress distribution has been determined in detail in Appendix A, an accurate weighting factor would not be possible because of the finite area inspected and averaged by a 1/4" diameter transducer. Because of this spatial averaging affect and the location of the transducer at data acquisition points, weighting factors of 2 at the ends, and 1 in the center, were used. In this particular technique, the six feature vectors are combined into a single feature vector by multiplying end values by 2 and center values by 1. The final feature vector calculated for each scan should, therefore, be representative of the entire bond quality, since the shear stress supported at the ends of the bond area is roughly twice that at the center.

CONCLUDING REMARKS

1. Significant accomplishments have been demonstrated in this report that advance the state of the art in ultrasonic adhesive bond inspection analysis. Special attention is given to the fact that 85% of all poor test specimens can be separated reliably from remaining test specimens.

2. The obvious peak to peak feature of the amplitude-time waveform was considered in this study. The feature is tremendously insensitive and difficult to use for predicting adhesive bond performance, in particular because of the noise variations in the ultrasonic data acquisition process.

3. The value of employing mechanics in this study is illustrated quite well. In particular, model analysis and shear distribution concepts are studied as an assist mechanism in the pattern recognition program of study.

4. The value of a computer automated data acquisition process and analysis technique are illustrated quite well because of test repeatability and computational efficiency.

5. The value of probability density estimator curve analysis, used in developing the pattern recognition algorithms, is illustrated quite well in obtaining insight to the feature values, sensitivities and pattern recognition areas that should receive attention.

RECOMMENDATIONS FOR FUTURE WORK

1. The transducer compensation problem should be carefully studied. Emphasis in this work was placed on developing an algorithm that was suitable for a specific transducer acceptance criteria. It is hoped that in the future, a suitable transducer compensation algorithm employing deconvolution concepts could be introduced so that the pattern recognition algorithm developed in this study could be applicable for many other transducer input situations. Certainly, in addition to transducer compensation, a suitable go - no go or acceptance criteria on a transducer will be required, but hopefully the acceptance criteria will not be as critical or as severe as that used in this study.

2. Confidence in a pattern recognition algorithm could certainly be obtained if more test specimens containing more quality control problems were considered in more detail. Additional data and test specimens are required to establish reasonable confidence levels.

3. The combined cohesive - adhesive test situation should certainly be considered even though problems associated with each, on an individual basis, seem promising for obtaining a solution.

4. Implementation potential of this pattern recognition algorithm and automated data acquisition analysis procedure should be considered, perhaps employing microprocessor technology. Both computational speed and storage requirements should be investigated in detail.

5. Additional tests should be conducted using similar techniques on various adhesive - substrate systems. Possibly the treatment of the critical composite to metal bond problem could be considered.

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β_1		β_2		β_3		DECISION
\geq	\leq	\geq	\leq	\geq	\leq	
2.05	2.50	1.10	1.355	*	*	Medium
2.05	2.80	1.355	1.7	*	*	Medium
2.50	3.05	1.10	1.355	*	*	High
2.50	2.875	1.75	2.05	*	*	High
2.50	2.60	2.05	2.45	*	*	High
2.60	2.95	2.05	2.45	*	*	Medium
2.95	3.05	2.40	2.55	*	*	High
2.90	3.05	1.1	2.55	*	*	Low
3.05	*	2.55	*	*	*	Out of Range
2.05	2.55	*	*	2.10	3.05	Medium
2.50	2.60	*	*	1.30	1.56	High
2.55	3.05	*	*	1.56	2.85	High
2.60	2.95	*	*	1.30	1.56	Medium
2.555	3.05	*	*	1.56	2.85	Low
3.05	*	*	*	3.05	*	Out of Range
*	*	1.10	1.70	2.10	2.97	Medium
*	*	1.75	2.55	1.56	2.80	High
*	*	1.90	2.07	1.20	1.56	High
*	*	2.07	2.55	1.20	1.40	High
*	*	2.07	2.55	1.40	1.56	Medium
*	*	2.55	*	3.05	*	Out of Range

* Data not Required

Table 1. Sequential Threshold Selection for Three Class Problem on Features β_1 , β_2 , and β_3 .

Specimen No.	Failure Load (pounds)	Actual Classification	Classification from Pattern Recognition Solution Fig. 15	
			Top	Bottom
37	4350	H	H	H
38	3600	H	H	H
39	2100	M	M	M
40	2450	M	M	M
41	4300	H	H	H
42	4050	H	H	H
43	2300	M	M	M
44	2750	M	M	M
45	400	L	L	L
46	500	L	L	L
47	300	L	L	L
48	400	L	L	L
49	4300	H	H	H
50	3100	M	M	M
51	2750	M	M	M
52	2650	M	M	M
53	2300	M	M	M
54	1850	L	H	H

L: 0 - 2000 lb.

M: 2000 - 3500 lb.

H: over 3500 lb.

Table 2. Summary of Series IV Failure Loads and Bond Classifications.

Specimen No.	Pattern Recognition Prediction		Failure Load (pounds)
	Top	Bottom	
67	H	L	3170
68	M	M	2950
70	M	H	2560
72	L	L	2110
73	OR	OR	3300
74	M	OR	2900
76	M	H	2390
77	OR	OR	1920
78	L	L	1940
93	H	H	3950
95	M	M	2700
96	M	M	2750
98	M	M	2400
101	M	OR	2860
102	M	M	2930
103	M	OR	2850
104	L	M	2520
105	M	M	3200
107	M	M	2620
108	M	M	2750
109	M	OR	3050

continued on next page

Table 3. Summary of Series V Bond Classification Predictions and Failure Loads.

Specimen No.	Pattern Recognition Prediction		Failure Load (pounds)
	Top	Bottom	
110	M	M	2870
118	L	L	1290
119	L	L	1340
120	M	M	3150
121	M	M	2310
122	M	M	2680
123	L	M	1020
124	L	L	1260

L: 0 - 2000 lb.

M: 2000 - 3500 lb.

H: over 3500 lb.

OR: Data could not be obtained within range to make a performance prediction

Table 3. Summary of Series V Bond Classification Predictions and Failure Loads.

	Failure Load Range			Total
	Low 0 - 2000 lb.	Medium 2000 - 3500 lb.	High over 3500 lb.	
Number of Possible Decisions	10	16	10	36
Number of Feature Vectors Out of Range	0	0	0	0
Number of Decisions Made	10	16	10	36
Number of Correct Decisions	8	16	10	34
Number of Incorrect Decisions	2	0	0	2
Percent Correct (Index of Performance)	80	100	100	94.4
Percent of Specimens Classified				100

Table 4A. Summary of Bond Classification Performance - Series IV

	Failure Load Range			Total
	Low 0 - 2000 lb.	Medium 2000 - 3500 lb.	High over 3500 lb.	
Number of Possible Decisions	12	44	2	58
Number of Feature Vectors Out of Range	2	6	0	8
Number of Decisions Made	10	38	2	50
Number of Correct Decisions	9	31	2	42
Number of Incorrect Decisions	1	7	0	8
Percent Correct (Index of Performance)	90	81.6	100	84
Percent of Specimens Classified				86.2

Table 4B. Summary of Bond Classification Performance - Series V

	Failure Load Range			Total
	Low 0 - 2000 lb.	Medium 2000 - 3500 lb.	High over 3500 lb.	
Number of Possible Decisions	22	60	12	94
Number of Feature Vectors Out of Range	2	6	0	8
Number of Decisions Made	20	54	12	86
Number of Correct Decisions	17	47	12	76
Number of Incorrect Decisions	3	7	0	10
Percent Correct (Index of Performance)	85	87	100	88
Percent of Specimens Classified				91.4

Table 4C. Summary of Bond Classification Performance - Series IV and Series V (Combined)

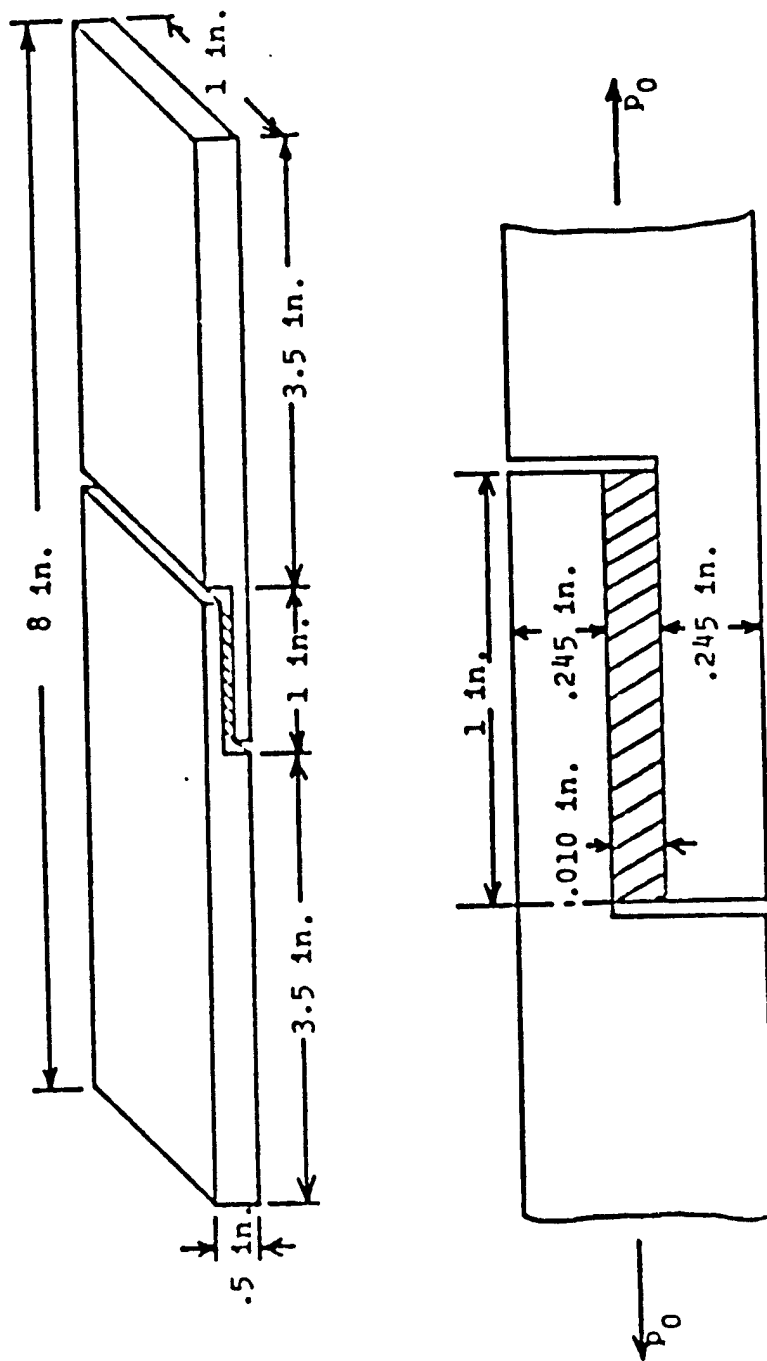


Figure 1. Step-Lap Joint Test Specimen (SI conversion: 1 in. = 25.4 mm)

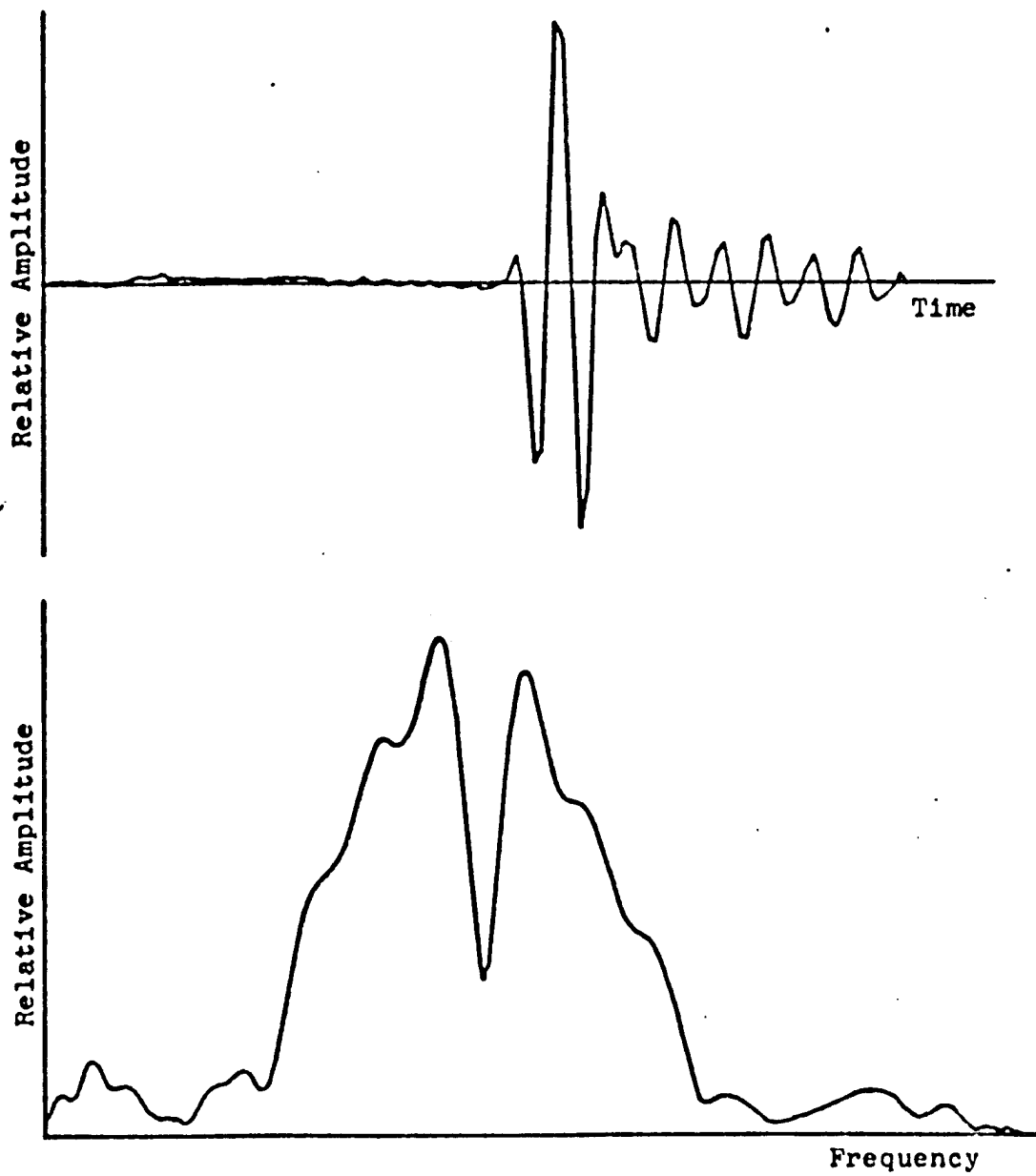


Figure 2A. Bond Echo Characteristics Obtained From
Computer Runs - 0% Area Reduction.

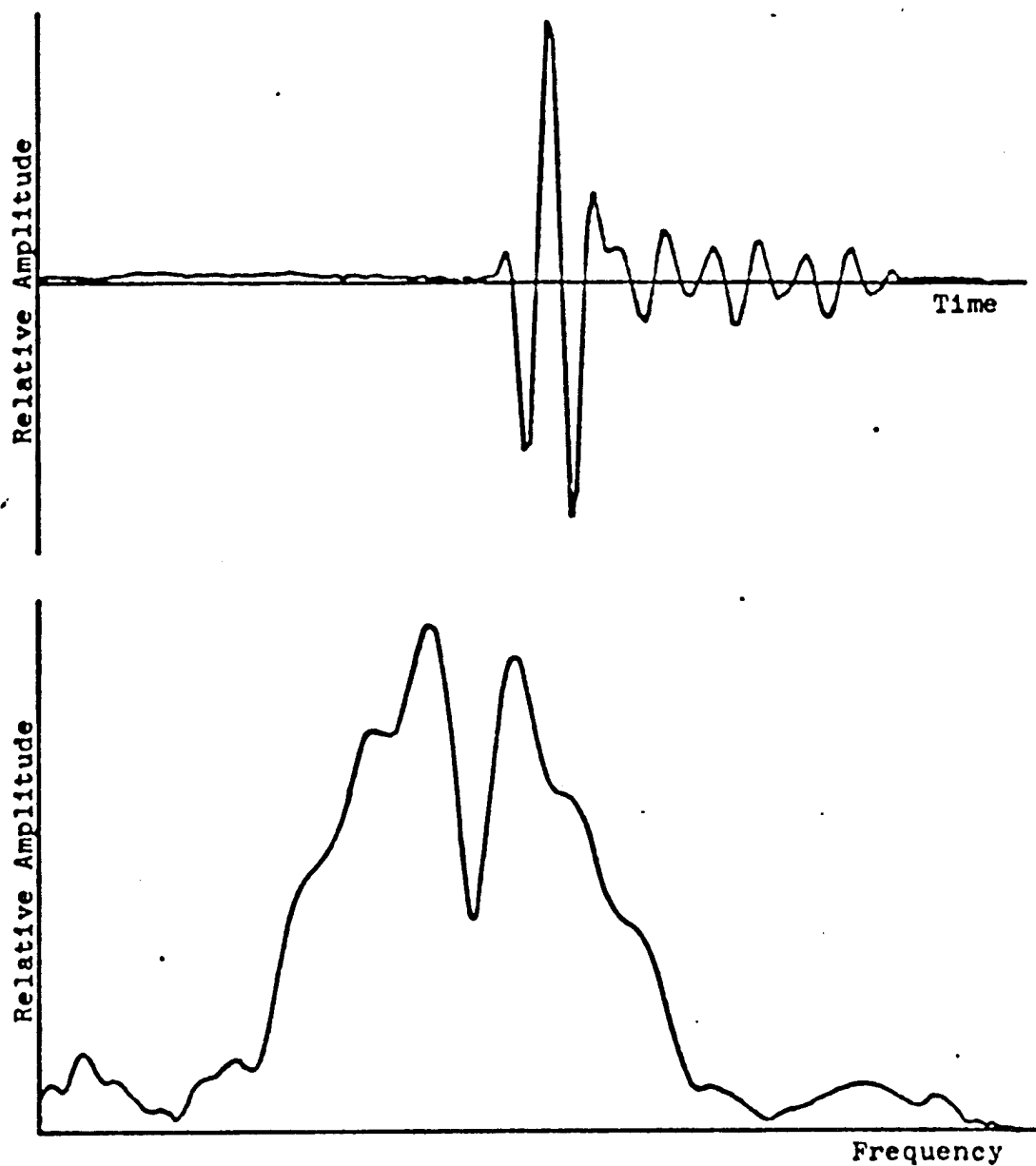


Figure 2B. Bond Echo Characteristics Obtained From Computer Runs - 25% Area Reduction.

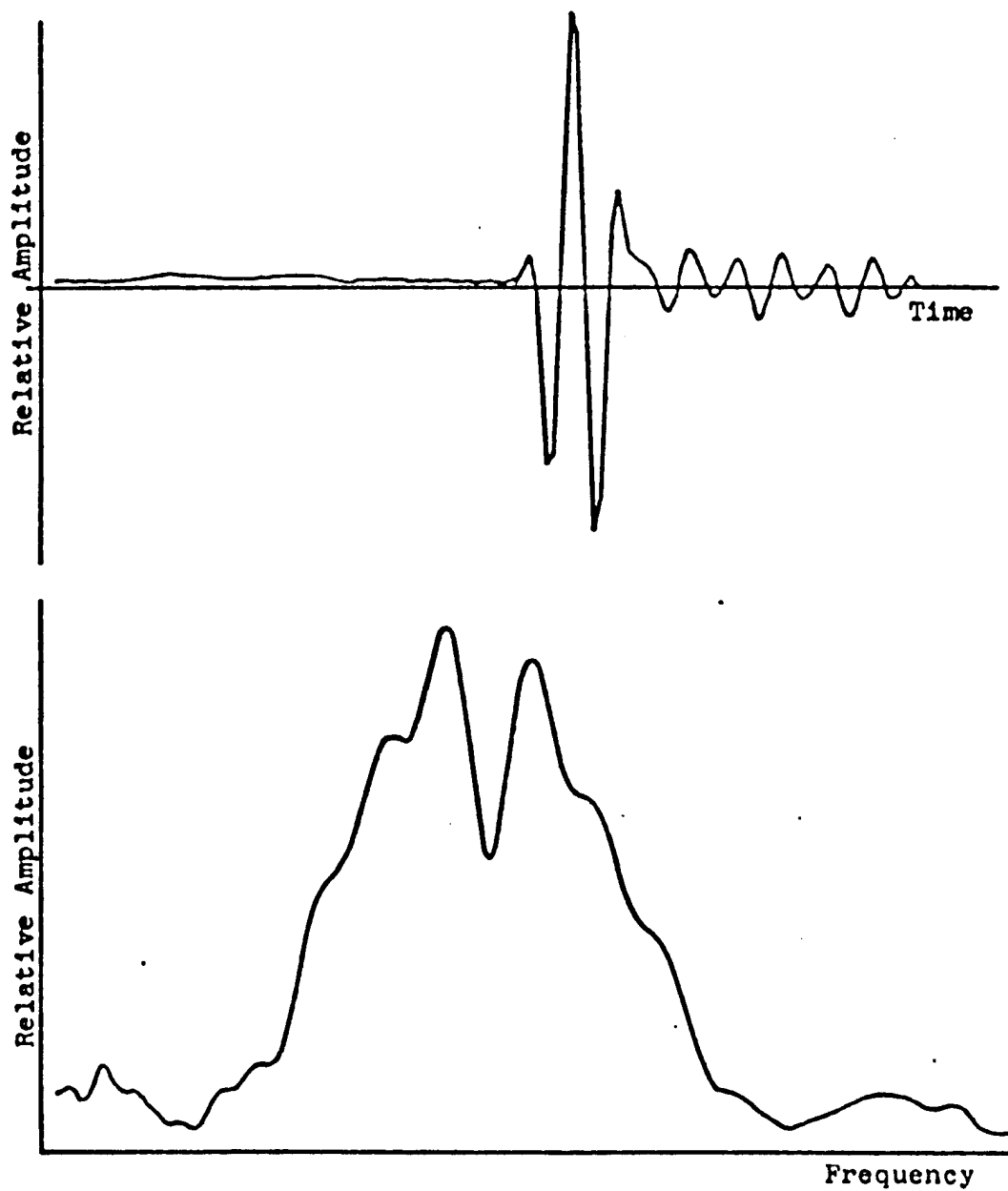


Figure 2C. Bond Echo Characteristics Obtained From
Computer Runs - 50% Area Reduction.

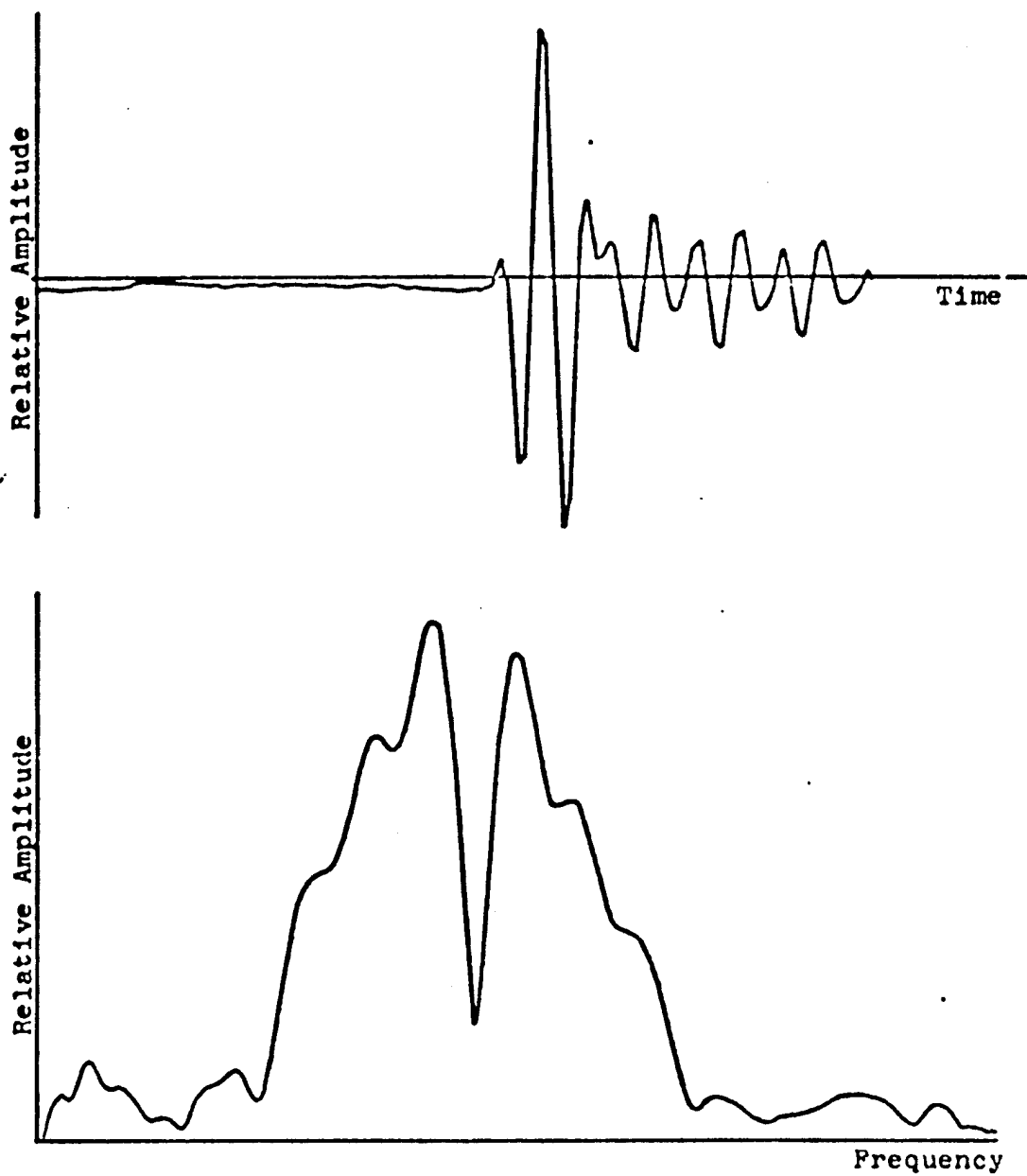


Figure 2D. Bond Echo Characteristics Obtained From
Computer Runs - 0% Area Reduction on Top
50% Area Reduction on Bottom

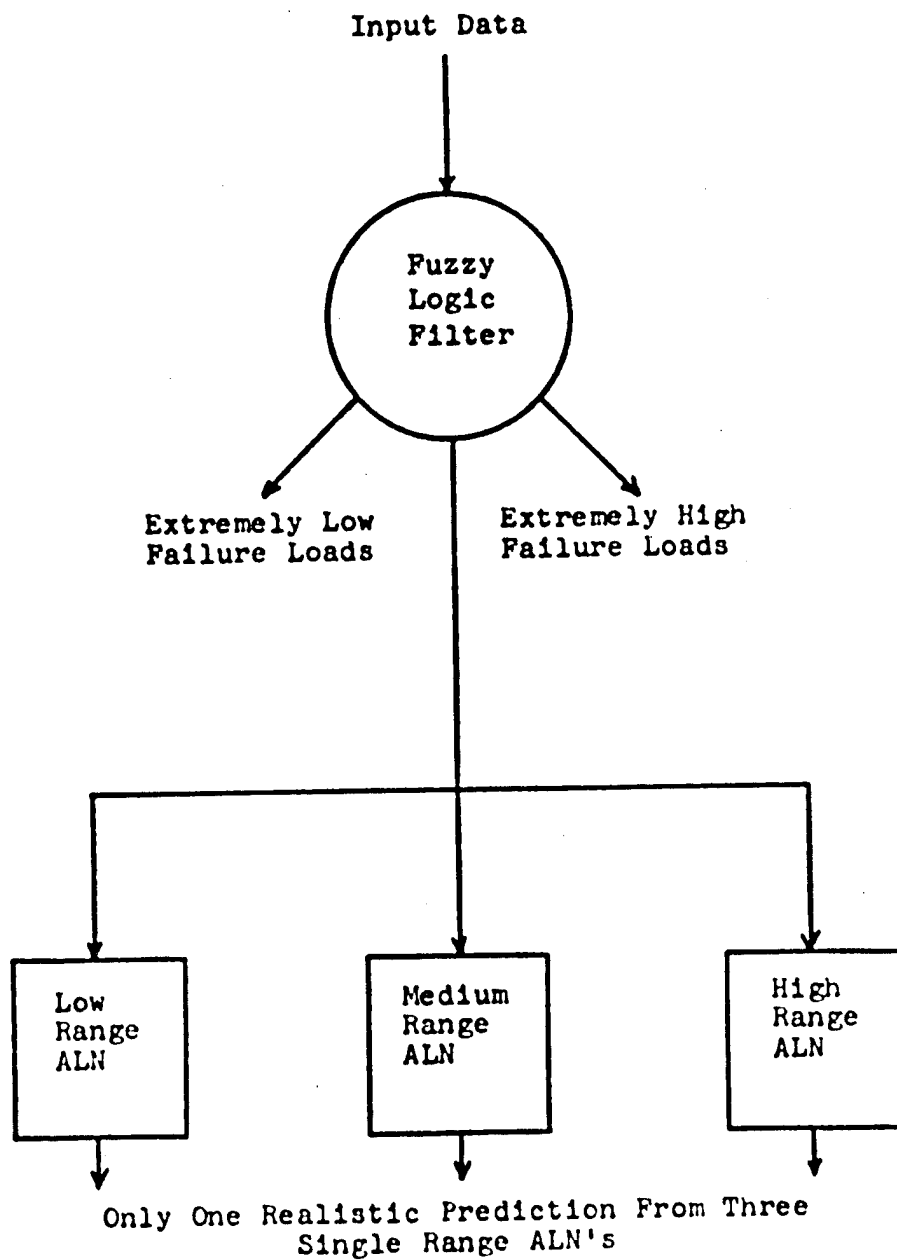
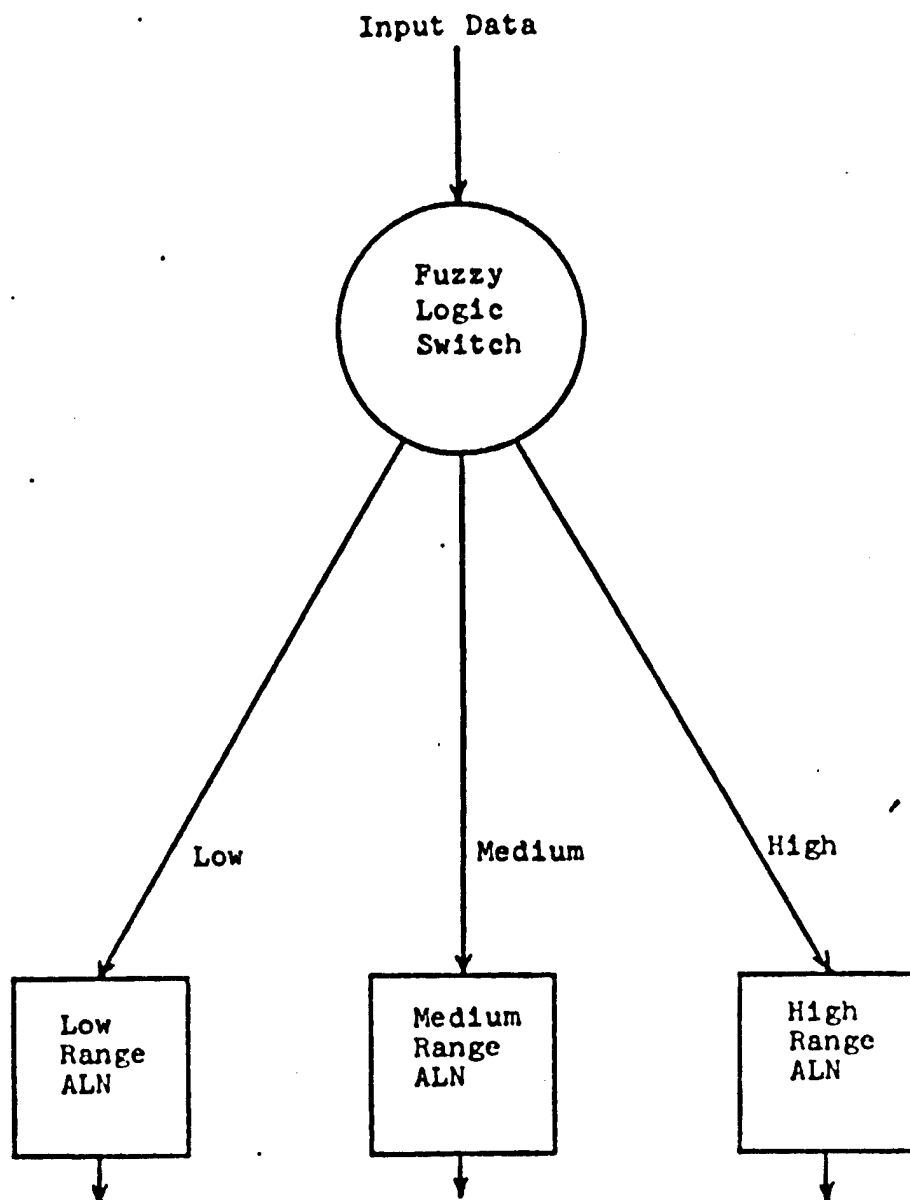


Figure 3. Pattern Recognition Approach Using Fuzzy Logic Filtering Technique.



Data Switched to Only One ALN.
ALN Provides Check on Fuzzy Logic Decision

Figure 4. Pattern Recognition Approach Using Fuzzy Logic Switching Technique.

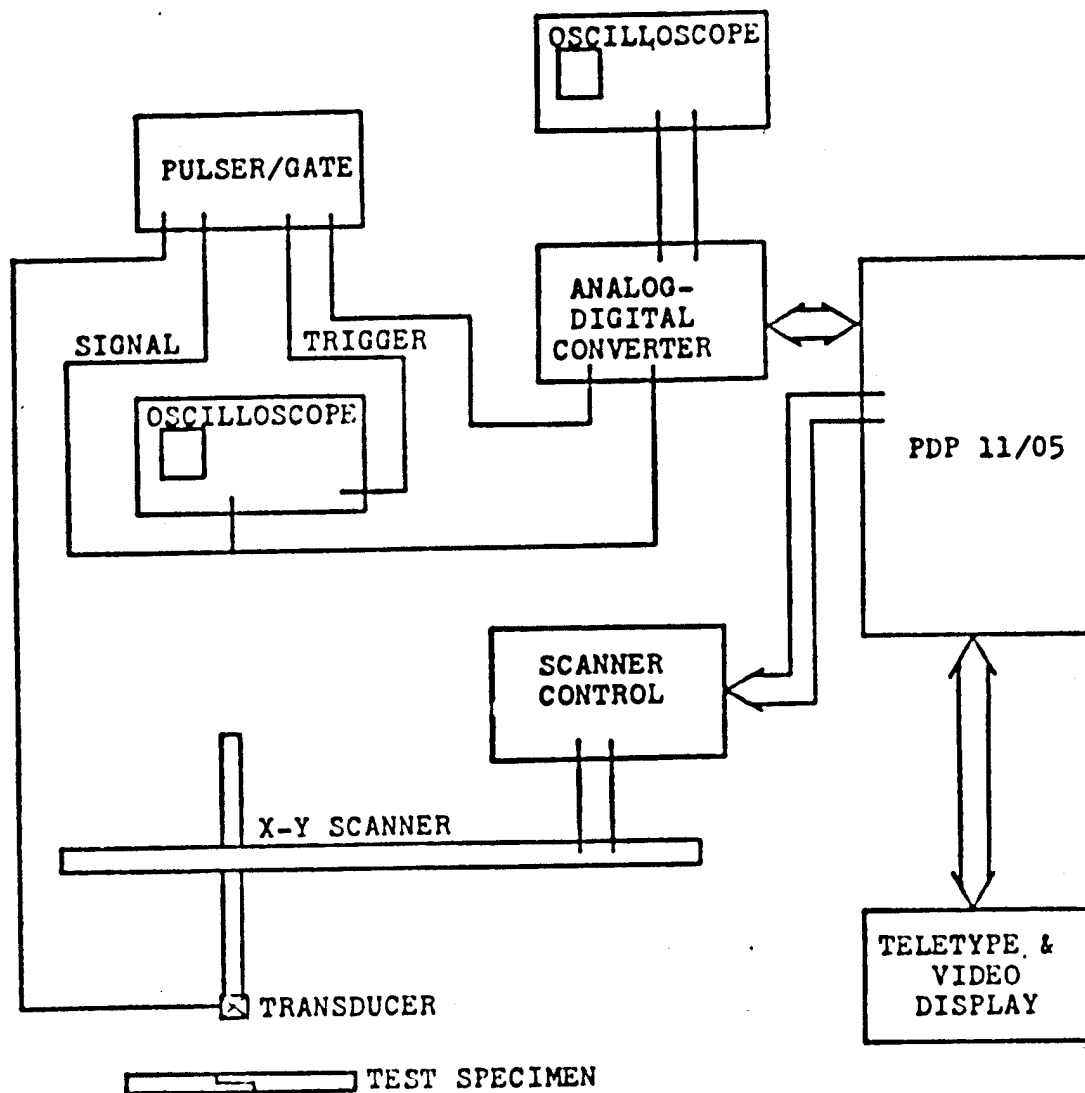


Figure 5. Block Diagram of the Fast Ultrasonic Data Acquisition and Analysis System.

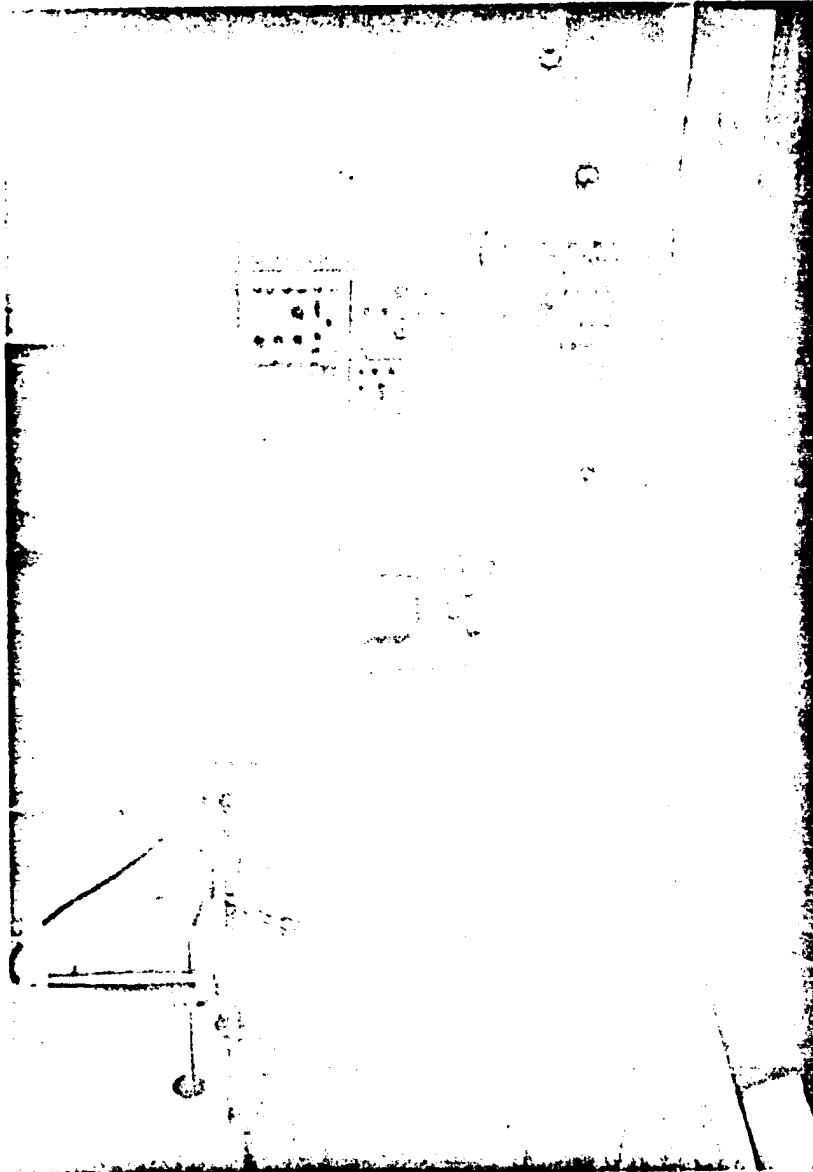


Figure 6. Photograph of the Ultrasonic Adhesive Bond Scanning System

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permit fully legible reproduction

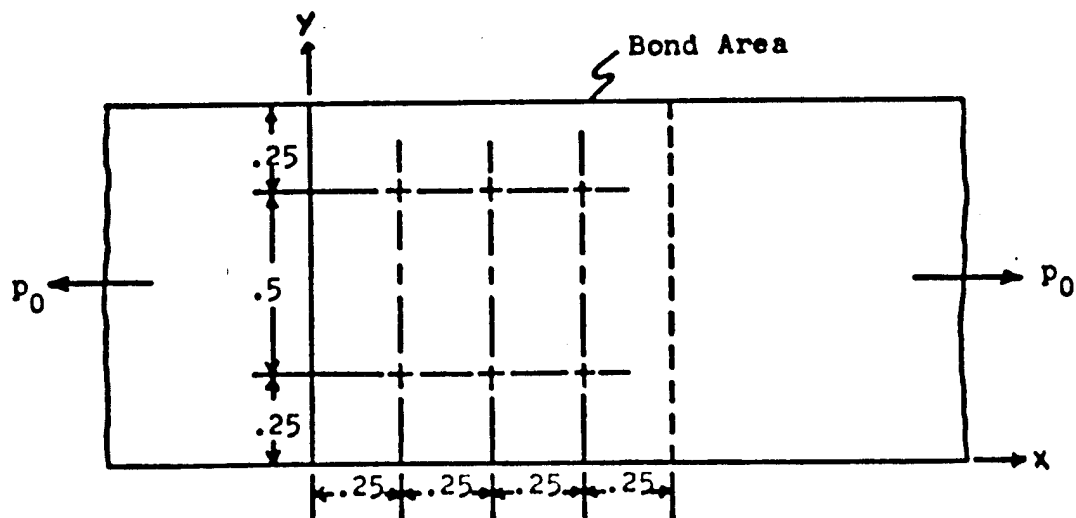
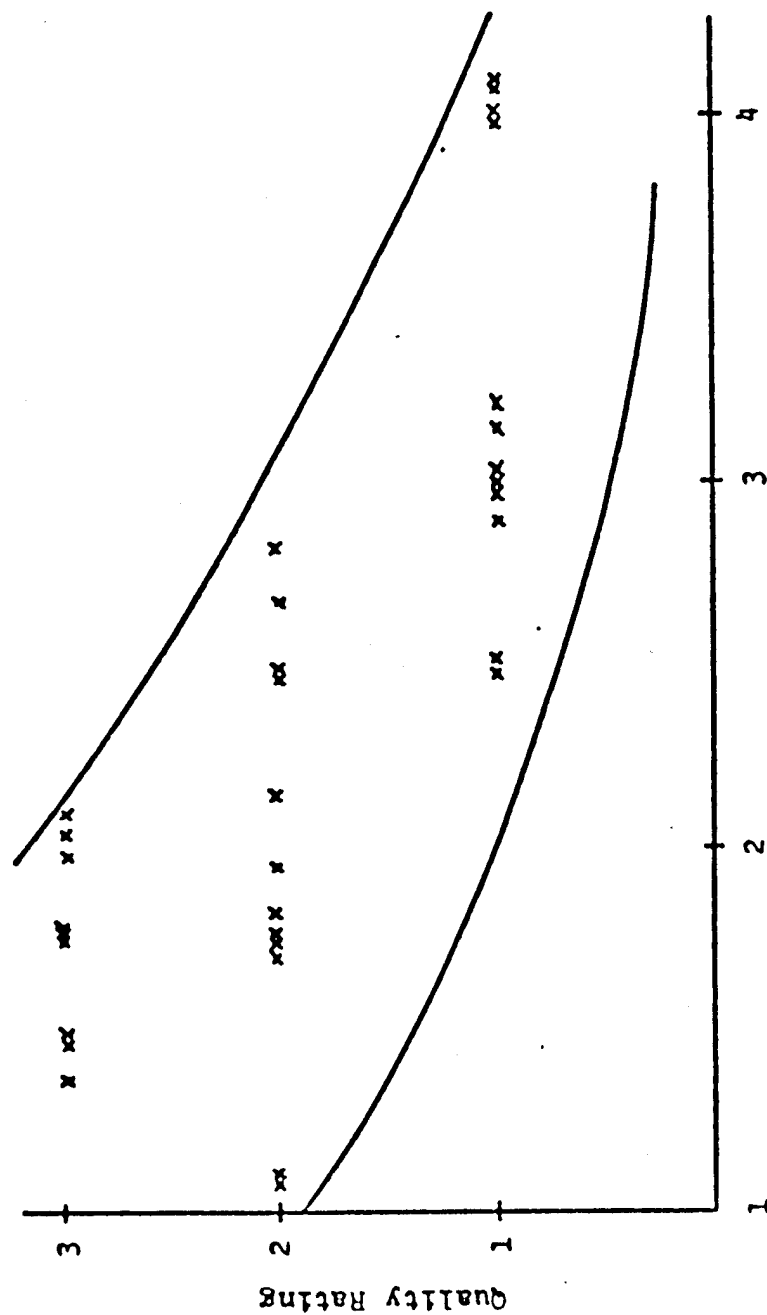


Figure 7. Spatial Location of Adhesive Bond Data Acquisition Points.



Failure Load (X 1000 lbs.)

Figure 8. Performance Characteristics of the Surface Preparation Adhesive Bond Specimens

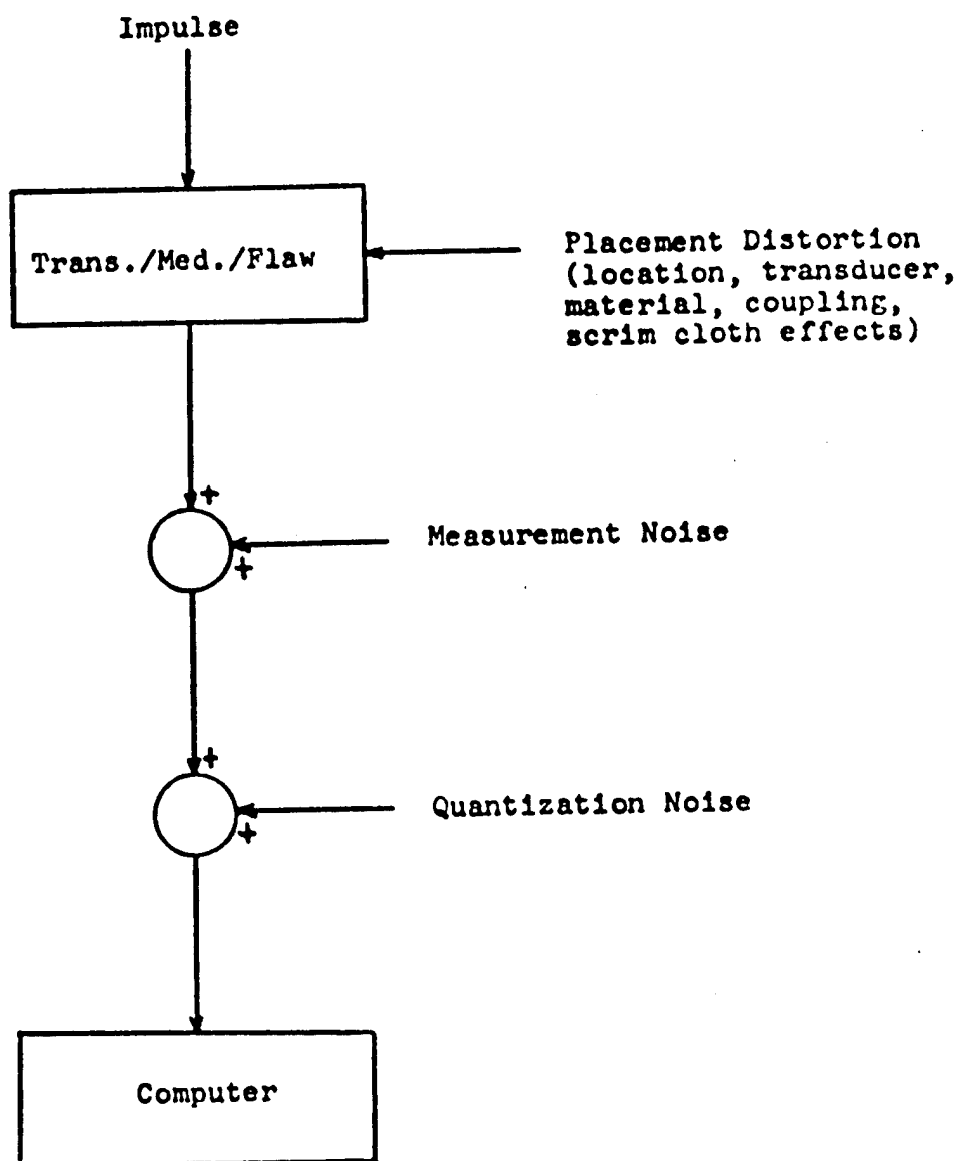


Figure 9. Primary Sources of Noise and Distortion in the Adhesive Bond Inspection Problem.

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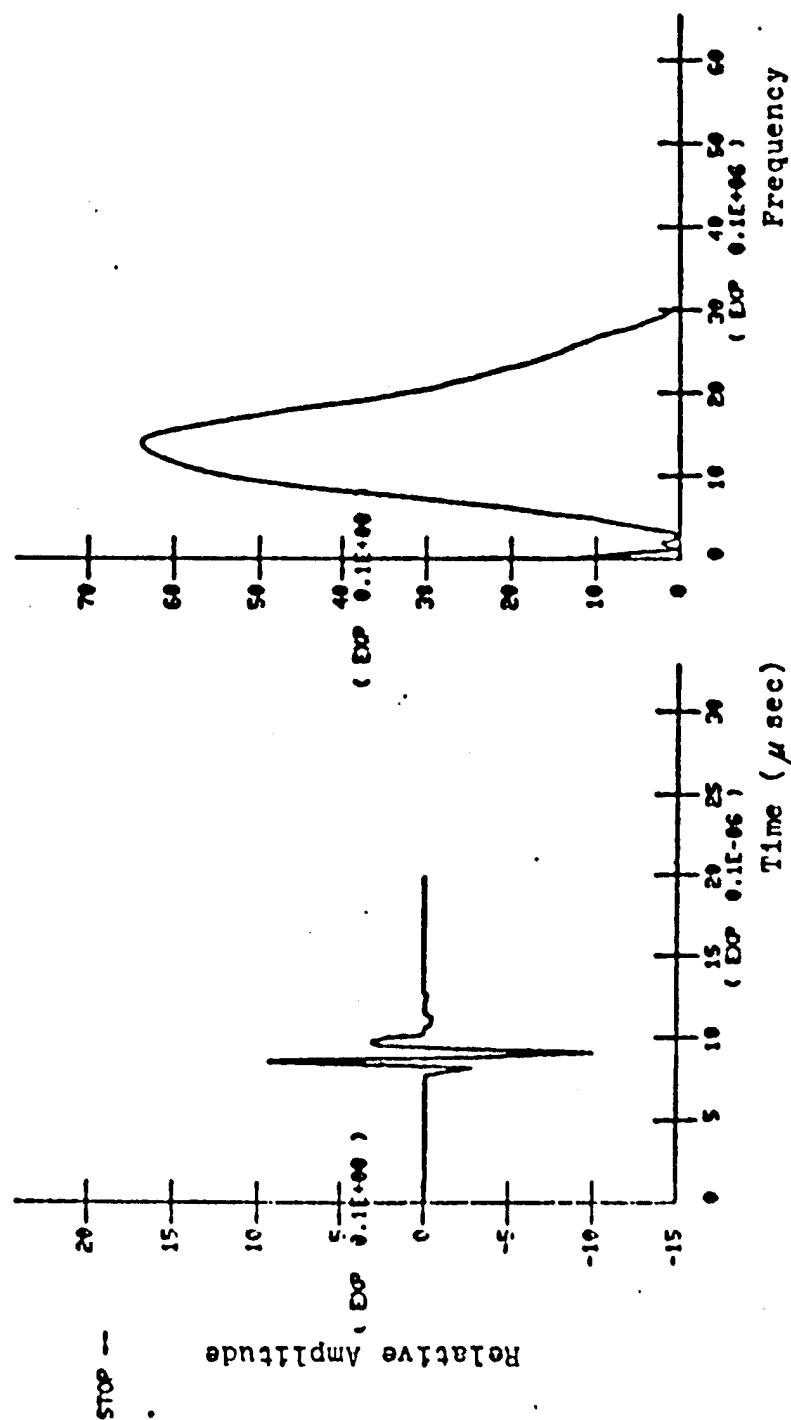


Figure 10. Amplitude-Time and Amplitude-Frequency Characteristics of the Reference Pulse.

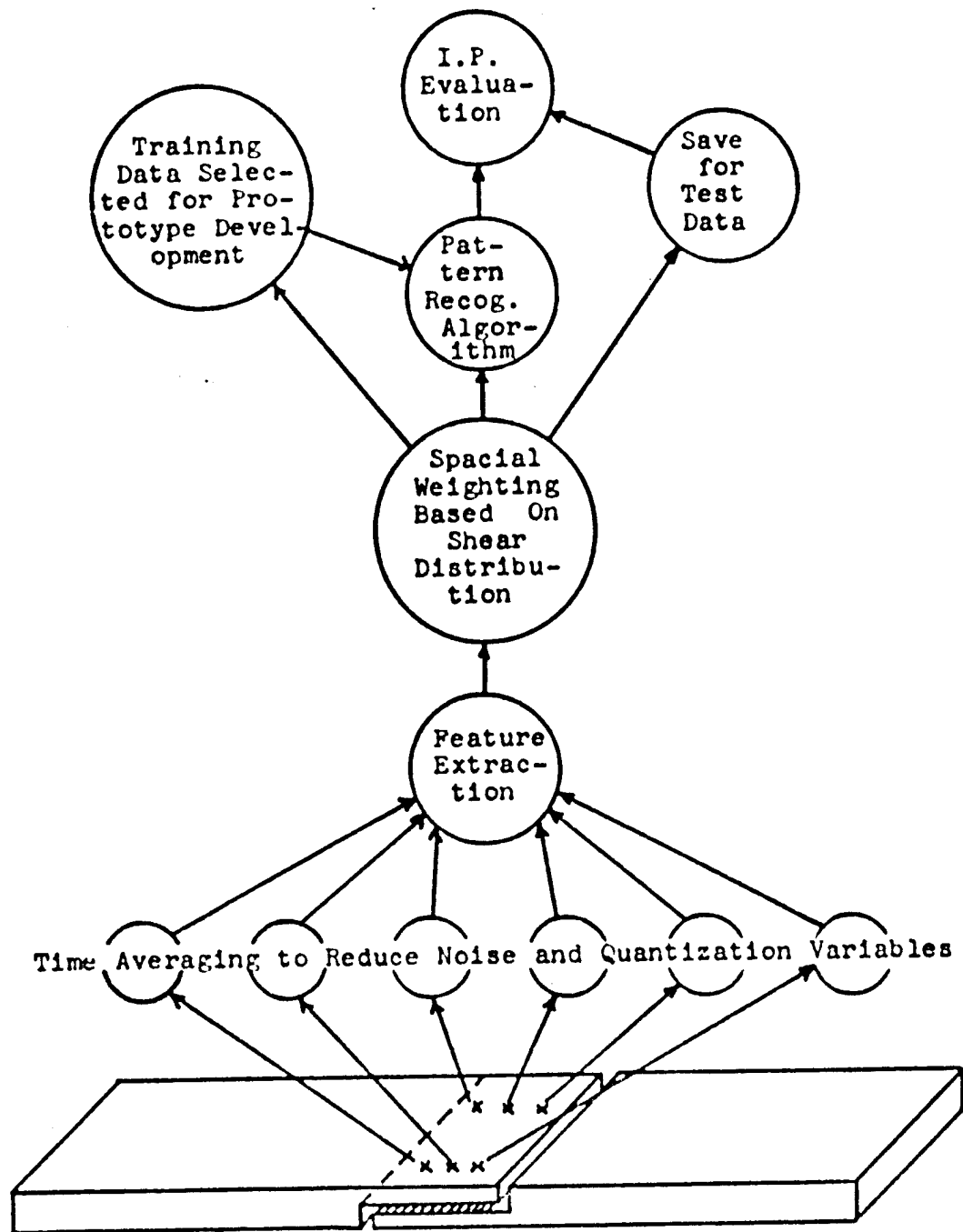
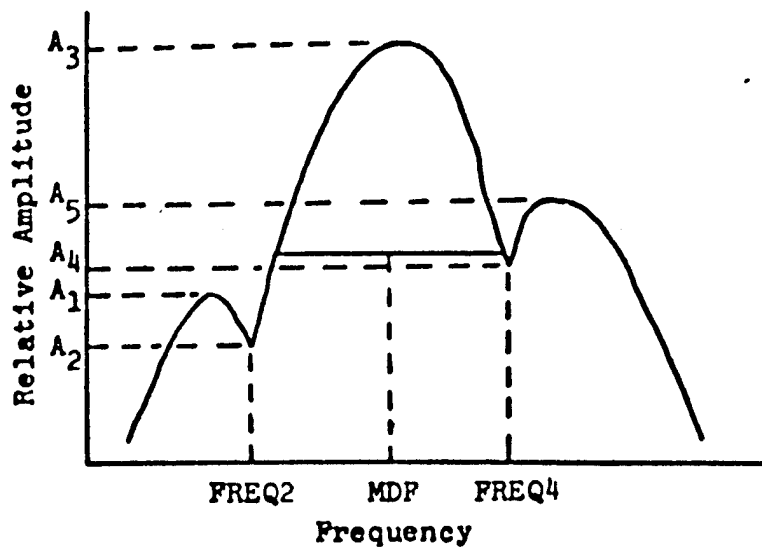


Figure 11. Collective Flow Chart of the Data Acquisition and Analysis Procedure.



$\beta_1 = |MDF - FREQ2|$ or $|MDF - FREQ4|$, whichever is smaller

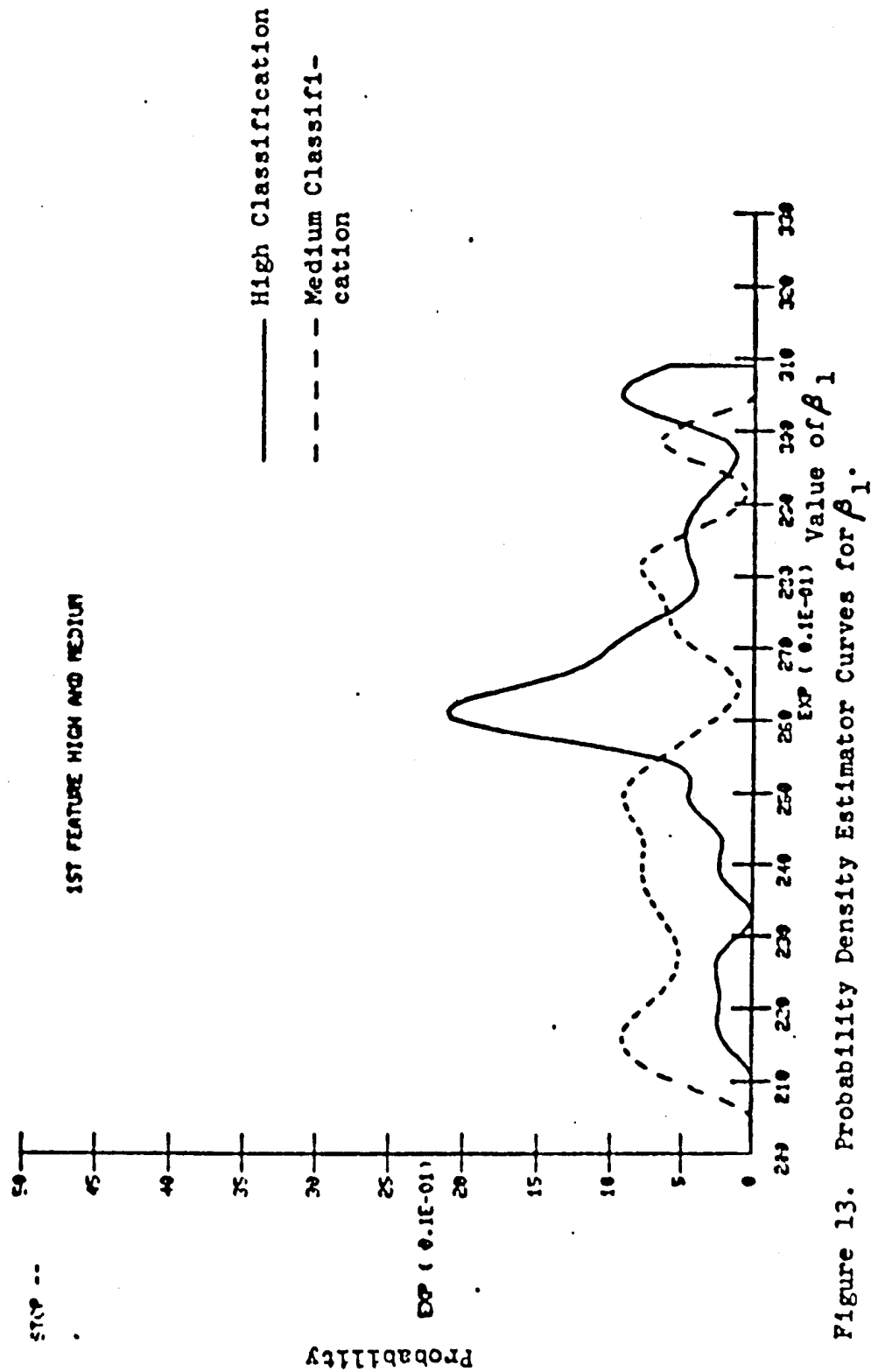
$\beta_2 = A_3/A_2$ if $\beta_1 = |MDF - FREQ2|$

$\beta_2 = A_3/A_4$ if $\beta_1 = |MDF - FREQ4|$

$\beta_3 = A_1/A_2$ if $\beta_1 = |MDF - FREQ2|$

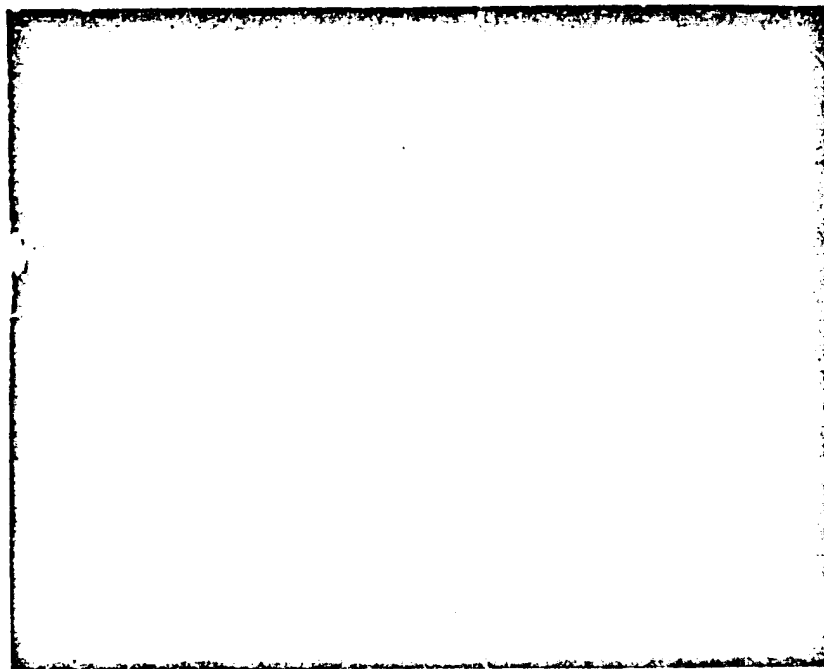
$\beta_3 = A_5/A_4$ if $\beta_1 = |MDF - FREQ4|$

Figure 12. Modified Feature Extraction Details for Series IV Test Specimens.



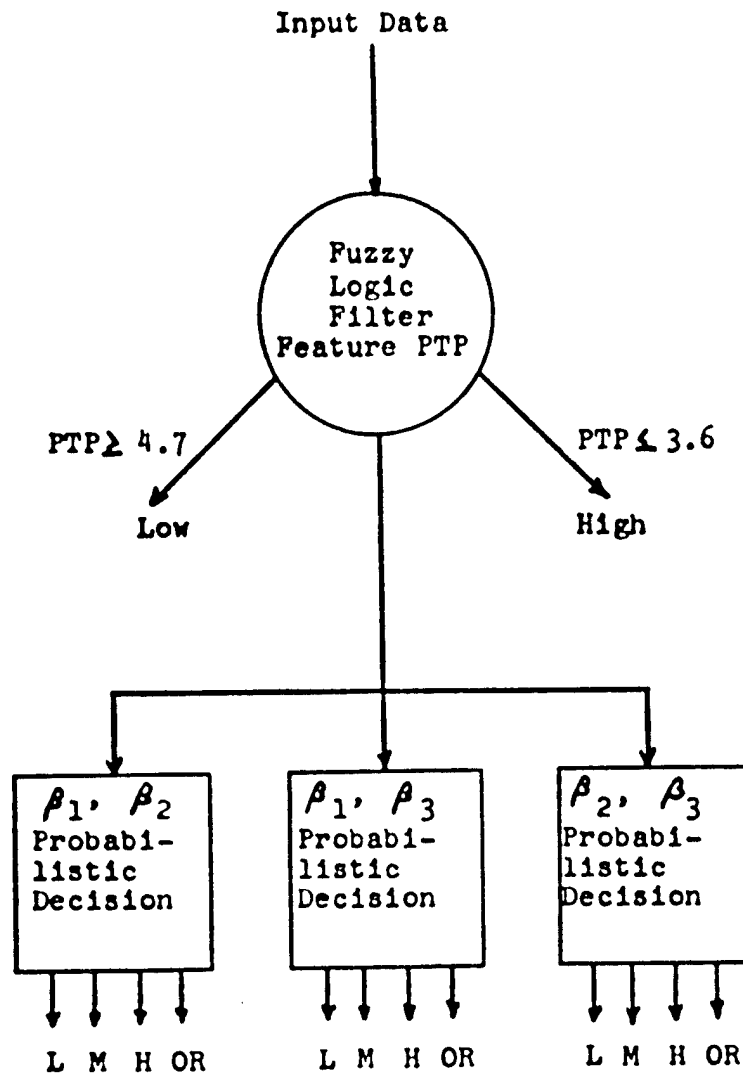


A. Adhesive Failure Surface



B. Cohesive Failure Surface

Figure 14. Photographs of Typical Failure Surfaces of Adhesive Bond Specimens. (Magnification 50X)



Each Decision Yields One Prediction

Three Predictions Yield One Through Committee Vote

Figure 15. Pattern Recognition Approach for Adhesive Bond Classification.

APPENDICES

APPENDIX A

SHEAR STRESS DISTRIBUTION IN A STEP-LAP JOINT

The spatial averaging technique required to condense the ultrasonic data from each bond scan is dependent on the shear stress distribution in the bond layer during loading. The distribution has been formulated by Erdogan and Ratwani [25] and is presented for the special case of an Aluminum-Adhesive-Aluminum step-lap joint.

Let homogeneous isotropic plates 1 and 2 be bonded with an adhesive in a step-lap joint as shown in Fig. A1. Stresses $\sigma_1(x)$ and $\sigma_2(x)$ in the plates and the resulting shear stress $\tau(x)$ on the interface must be calculated with the structure under a uniform tensile load p_0 . The following assumptions will be made:

1. The adhesive thickness h_3 is small compared to plate thickness enabling the entire structure to be considered to be in a state of plane stress. In the case treated in this study, adhesive thickness varies from .005 in. to .010 in. with plate thicknesses of .25 in.

2. The strain in the substrates in the z-direction is assumed to be zero.

If $p_1(x)$ and $p_2(x)$ are the resultant forces/unit width acting in the x-direction and $u_1(x)$ and $u_2(x)$ the displacements in the x-direction in plates 1 and 2, respectively, equilibrium of plate 2 and the adhesive yields

$$p_2(x) = \int_0^x \tau(x) dx \quad (A1)$$

where

$$\tau(x) = \frac{G}{h_3} (u_2 - u_1) \quad (A2)$$

Assuming $\bar{\epsilon}_z = \epsilon_{1z} = \epsilon_{2z} = 0$,

with

$$\begin{aligned} p_1(x) &= p_0 - p_2(x) \\ \sigma_1 &= p_1/h_1 \\ \sigma_2 &= p_2/h_2 \end{aligned} \quad (A3)$$

and with stress-strain relations, we obtain

$$\epsilon_1(x) = \frac{1-\nu_1^2}{E_1 h_1} [p_0 - p_2(x)]$$

and

$$\epsilon_2(x) = \frac{1-\nu_2^2}{E_2 h_2} p_2(x) \quad (A4)$$

From (A1), (A2), and (A4) we obtain

$$\frac{d^2 p_2}{dx^2} - \alpha^2 p_2 = \beta p_0 \quad (A5)$$

where

$$\alpha^2 = \frac{G_3}{h_3} \left[\frac{1-\nu_1^2}{E_1 h_1} + \frac{1-\nu_2^2}{E_2 h_2} \right]$$

$$\beta = -\frac{G_3}{h_3} \frac{1-\nu_1^2}{E_1 h_1}$$

Assuming end surfaces to be traction-free

$$p_2(0) = 0$$

$$p_2(l) = p_0$$

the solution to (A5) may be obtained as

$$p_2(x) = \frac{\beta p_0}{\alpha^2} \left[\cosh \alpha x - 1 + (1 - \cosh \alpha l + \frac{\alpha^2}{\beta}) \frac{\sinh \alpha x}{\sinh \alpha l} \right] \quad (A6)$$

$$\tau(x) = \frac{dp_2}{dx} = \frac{\beta p_0}{\alpha} \left[\sinh \alpha x + (1 - \cosh \alpha l + \frac{\alpha^2}{\beta}) \frac{\cosh \alpha x}{\sinh \alpha l} \right] \quad (A7)$$

Defining

$$h_3 = 6, \quad \alpha = A/\sqrt{\epsilon}, \quad \beta = -B/\epsilon \quad (A8)$$

where A and B are positive constants, (A7) becomes

$$\tau(x) = \frac{-p_0 B}{A} \frac{1}{\sqrt{\epsilon}} \left[-\frac{\cosh \alpha (l-x)}{\sinh \alpha l} + (1 - \frac{A^2}{B}) \frac{\cosh \alpha x}{\sinh \alpha l} \right] \quad (A9)$$

for two identical isotropic plates

$$\alpha^2 = \frac{2G_3(1-\nu_1^2)}{h_3 E_1 h_1} \therefore A^2 = \alpha^2 h_3 = \frac{2G_3(1-\nu_1^2)}{E_1 h_1} \quad (A10)$$

$$\beta = -\frac{G_3(1-\nu_1^2)}{h_3 E_1 h_1} \therefore B = -\beta h_3 = \frac{G_3(1-\nu_1^2)}{E_1 h_1} \quad (A11)$$

and

$$\tau(x) = \frac{p_0 A}{2 \sqrt{h_3} l} \left[\frac{\cosh \alpha(l-x) + \cosh \alpha x}{\sinh \alpha l} \right] \quad (A12)$$

where

$$A = (\alpha^2 h_3)^{1/2}$$

$$\alpha = \left[\frac{2G_3}{h_3} \left(\frac{1-\nu_1^2}{E_1 h_1} \right) \right]^{1/2} \quad (A13)$$

This result may be plotted for both substrates and by superposition, the shear stress in the adhesive layer is shown in Fig. A2.

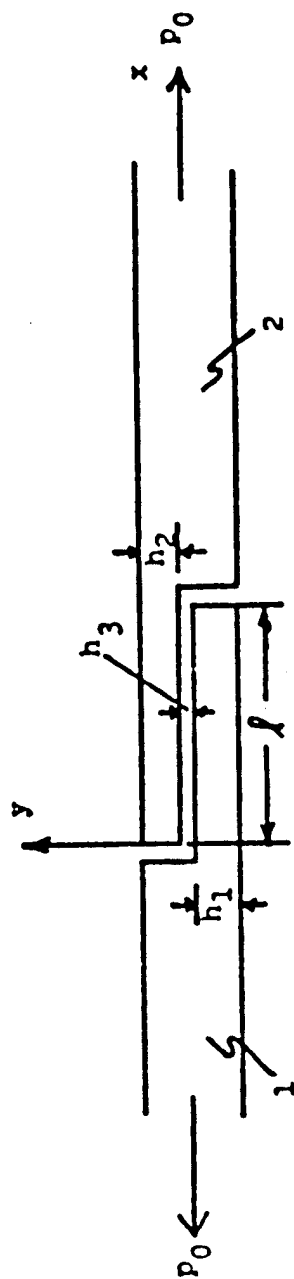


Figure A1. Step-Lap Joint Coordinate System.

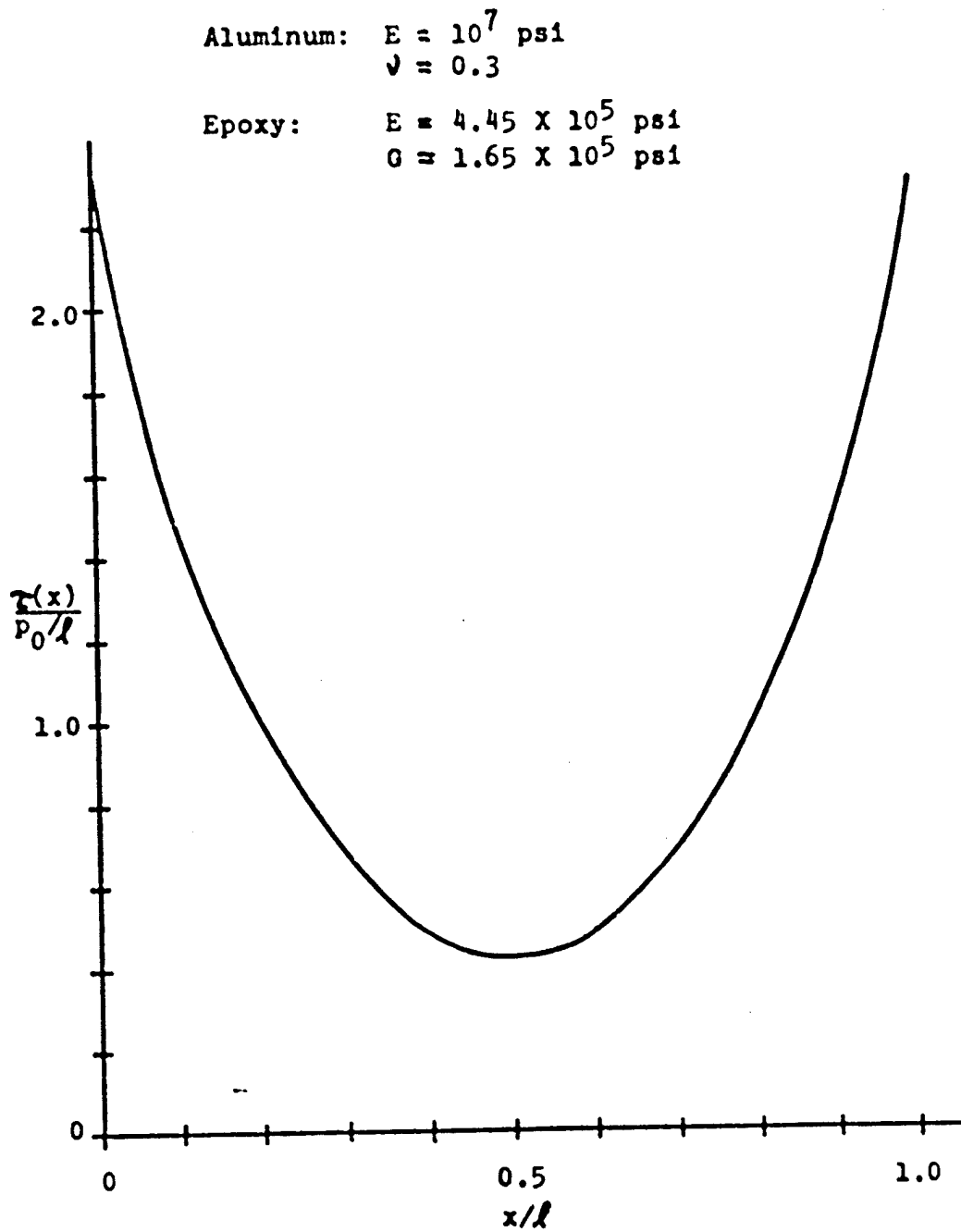


Figure A2. Shear Stress in an Aluminum-Aluminum Step-Lap Joint. (1 psi = 6.8 kN/m²)

APPENDIX B

SPLINE FUNCTION INTERPOLATION REVIEW

Smooth curve interpolation through fixed points by high degree polynomials may be characterized by unwanted oscillation.

A much more desirable curve is produced by using a French curve or by a flexible elastic bar, a spline bar. An interpolation process which has been mathematically modelled after the spline bar and then mathematically generalized into a set of functions are the spline functions. The Natural Cubic Spline is a function that duplicates the same curve as a perfectly elastic bar forced to pass through a set number of specified points on a plane surface.

Cubic Spline

Given a series of points x_i ($i = 0, 1, \dots, N$), and a functional value $y(x_i)$ at each point, we wish to find a cubic polynomial that fits two adjacent points x_i and x_{i+1} . (Note that these points do not have to be evenly spaced.) Let this function be

$$F_i(x) = C_0 + C_1x + C_2x^2 + C_3x^3,$$

$$\text{for } x_i \leq x \leq x_{i+1}$$

(B1)

There are only two obvious conditions the function $F_1(x)$ must satisfy. These conditions are:

$$F_1(x_1) = y(x_1) \text{ and} \quad (B2)$$

$$F_1(x_{i+1}) = y(x_{i+1}) \quad \text{for } i = 1, 2, 3, \dots, N$$

Since the polynomial is determined by four unique coefficients, two more conditions may be chosen to obtain the objective of "smoothness" or "best fit". Noting that the first derivative is the slope of the curve and that the second derivative is the curvature of the curve, an effective approach would be to match first and second derivatives of adjacent intervals. These two conditions may be mathematically expressed as

$$F'_1(x_1) = F'_{i-1}(x_1) \text{ and} \quad (B3)$$

$$F''_1(x_1) = F''_{i-1}(x_1) \text{ where } F_{i-1}(x) \text{ is defined on the interval } x_{i-1} \leq x \leq x_i.$$

This matching procedure can be carried out for each interval contained in $x_0 \leq x \leq x_n$. (Note: the endpoints will be treated separately later).

Let the Function $S(x)$ be defined as the union of all the cubic polynomials $F_1(x)$ where each $F_1(x)$ is defined only on the interval $x_i \leq x \leq x_{i+1}$. Then, the second derivative is linear over each interval. (The second derivative of a cubic is a straight line.) This implies

$$S''(x) = S''(x_1) + \frac{x-x_1}{x_{i+1}-x_1} \left[S''(x_{i+1}) - S''(x_1) \right] \quad (B4)$$

Integrating the above expression twice, and applying the conditions

$$S(x_1) = y(x_1) \text{ and}$$

$$S(x_{i+1}) = y(x_{i+1}) \quad \text{for } x_1 \leq x \leq x_{i+1} \quad (B5)$$

The function $S(x)$ may be expressed mathematically as

$$\begin{aligned} S(x) = F_1(x) = & \frac{S''(x_1)}{6} \left[\frac{(x_{i+1}-x)^3}{\Delta x_1} - \Delta x_1(x-x_1) \right] \\ & + \frac{S''(x_{i+1})}{6} \left[\frac{(x-x_1)^3}{\Delta x_1} - \Delta x_1(x-x_1) \right] \\ & + y(x_1) \left[\frac{x_{i+1}-x}{\Delta x_1} \right] + y(x_{i+1}) \left[\frac{x-x_1}{\Delta x_1} \right] \end{aligned} \quad (B6)$$

where $\Delta x_1 = x_{i+1} - x_1$.

Applying the conditions from (B3)

$$F'_1(x_1) = F'_{i-1}(x_i) \text{ and } F''_1(x_1) = F''_{i-1}(x_i)$$

These conditions state that $S''(x_1)$ is the same when approached from either side of the coordinate (x_1, y_1) , a

set of (N-1) linear equations is obtained. These equations are as follows:

$$\left[\frac{\Delta x_{i-1}}{\Delta x_i} \right] S''(x_{i-1}) + \left[\frac{s(x_{i+1} - x_{i-1})}{\Delta x_i} \right] S''(x_i) + S''(x_{i+1})$$

$$= 6 \left[\frac{y(x_{i+1}) - y(x_i)}{(\Delta x_i)^2} - \frac{y(x_i) - y(x_{i-1})}{(\Delta x_i)(\Delta x_{i-1})} \right]$$

$$\text{for } i = 1, 2, 3, \dots, N-1 \quad (B7)$$

For the special case where equal spacing exists between all points, Δx is constant.

$$S''(x_{i-1}) + 4S''(x_i) + S''(x_{i+1})$$

$$6 \left[\frac{y(x_{i+1}) - 2y(x_i) + y(x_{i-1}))}{(\Delta x_i)^2} \right] \quad (B8)$$

There are N-1 equations, but N+1 unknowns exists $S''(x_0)$, $S''(x_1)$, ..., $S''(x_N)$. One simply specified $S''(x_0) = 0$ and $S''(x_N) = 0$. (Physically, this is equivalent to allowing an elastic bar to remain straight beyond the region of interest.) Now the set of equations may be solved.

VITA

VITA

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Publications

Rose, J.L. and Raisch, J.W., "A Model for Ultrasonic Pipe Inspection", Materials Evaluation, 1973.

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